Water Standards and Studies Report No. 86-8

Water Chemistry Changes Associated With Hydroelectric Development in Northern Manitoba: The Churchill, Rat, Burntwood, and Nelson Rivers

Manitoba
Environment and
Workplace Safety
and Health

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MANITOBA ENVIRONMENT AND WORKPLACE SAFETY AND HEALTH
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Summary

The Churchill River diversion and Lake Winnipeg regulation in northern Manitoba have increased the hydroelectric generating capacity of the Burntwood and Nelson river systems. The diversion has resulted in increased flows and water levels along the Burntwood and lower Nelson rivers and reduced flows in the lower Churchill River. Lake Winnipeg regulation has affected water levels and flows in the upper Nelson River through construction of control structures and channels between the outlet lakes of Lake Winnipeg.

The effects of these projects on water chemistry were investigated by comparing water chemistry data from before mid-1976 with data collected after mid-1976. Mid-1976 was chosen as the comparison date because it approximated the time the projects became operational. Student's t-test was used to determine if differences existed between pre- and post-operational means of twenty water chemistry parameters at ten sites along rivers affected by the projects.

Granville Lake on the Churchill River is upriver of the Churchill River diversion and was used as a reference site. Six parameters showed statistically significant changes at Granville Lake after mid-1976. These changes may have been caused by changes in discharge from Reindeer Lake reservoir in Saskatchewan, or variation in a natural phenomenon such as precipitation.

Water chemistry changes along the path of the diversion were due mainly to flooding and the increased flow of softer Churchill River water. Most of the water chemistry changes at the community of

South Indian Lake were a result of the increased flow of Churchill River water past a previously sheltered section of Southern Indian Lake. These changes included a reduction of total coliform bacteria. Turbidity increased significantly because of flooding and erosion in Southern Indian Lake. Water chemistry near the community of Nelson House was relatively stable, a consequence of its location off the main flow of the diversion. However, there was an increase in turbidity which was likely due to flooding. Changes in water chemistry in the Burntwood River at Thompson were mostly due to the increased flow of softer Churchill River water.

At Split Lake, located at the junction of the Burntwood and Nelson rivers, water chemistry changes were due to both the increased flow of softer Churchill River water and changes in the upper Nelson River. Changes included an increase in turbidity and a decrease in conductivity because of the increased flow of turbid, softer water along the Burntwood River. Total organic carbon increased because of an increase in total organic carbon in the upper Nelson River.

Water chemistry changes in the upper Nelson River included increases in turbidity, total organic carbon, and total inorganic carbon. These water chemistry changes may have been due to Lake Winnipeg regulation. The upper Nelson sites examined were Sipiwesk Lake, Cross Lake settlement, and Norway House.

Chemistry in the lower Churchill River changed because of increased turbidity from flooding and erosion in Southern Indian Lake and because local drainage had more influence on water chemistry once

most of the Churchill River flow was diverted southward. Lower Churchill River sites examined were Missi Falls and the Churchill water intake.

Changes in drinking water quality were mixed. This was observed at South Indian Lake community where turbidity increased but total coliform bacteria decreased after diversion. All surface waters in Manitoba are susceptible to uncontrolled microbial contamination (i.e. by wildlife) so minimum treatment consisting of disinfection is required prior to human consumption. The bacterial and turbidity data suggest that additional water treatment is now required for water drawn from all the sites considered, except the Churchill River at Granville Lake and Footprint Lake near Nelson House. However, the data suggest that this additional degree of treatment was warranted at most sites even before development.

Predictions of water chemistry changes caused by the hydroelectric projects were generally good, especially those related to changes in water flow. Some predictions could not be tested because of insufficient data. Continued monitoring of water chemistry is recommended to improve our understanding of the effects of hydroelectric development in northern Canada.

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1.0 Introduction

Hydroelectric development in northern Manitoba has included partial diversion of the Churchill River into the more southern Nelson River. This was accomplished by building a dam across the northern outlet of Southern Indian Lake and diverting the bulk of the river flow through a southern channel into the Rat-Burntwood river system (Figure 1). The diversion has caused increased flows and water levels in rivers and lakes along the diversion path and reduced flow in the lower Churchill River. Effects of the project on Southern Indian Lake have included increased shoreline erosion, elevated lake turbidity, increased mercury levels in fish, and the collapse of the lake whitefish fishery (Hecky et al. 1984). Some effects of the diversion were anticipated by the Lake Winnipeg, Churchill and Nelson Rivers (LWCNR) Study Board (1975) but other, mainly biological effects were poorly predicted (Hecky et al. 1984).

Hydroelectric development has also involved regulation of Lake Winnipeg. Lake regulation was achieved by building control structures and digging channels between Lake Winnipeg and its outlet lakes. Effects of Lake Winnipeg regulation have included water level changes, high turbidity, and decreases in whitefish catch in Cross Lake (Bodaly et al. 1984a). Predictions of the effects of Lake Winnipeg regulation were limited, and effects of the regulation on water chemistry have not been assessed.

The present study examines changes in water chemistry associated with the diversion and Lake Winnipeg regulation by comparing early chemical data with data collected after the projects became operational. When possible the changes seen were compared with predictions made by the LWCNR (1975).

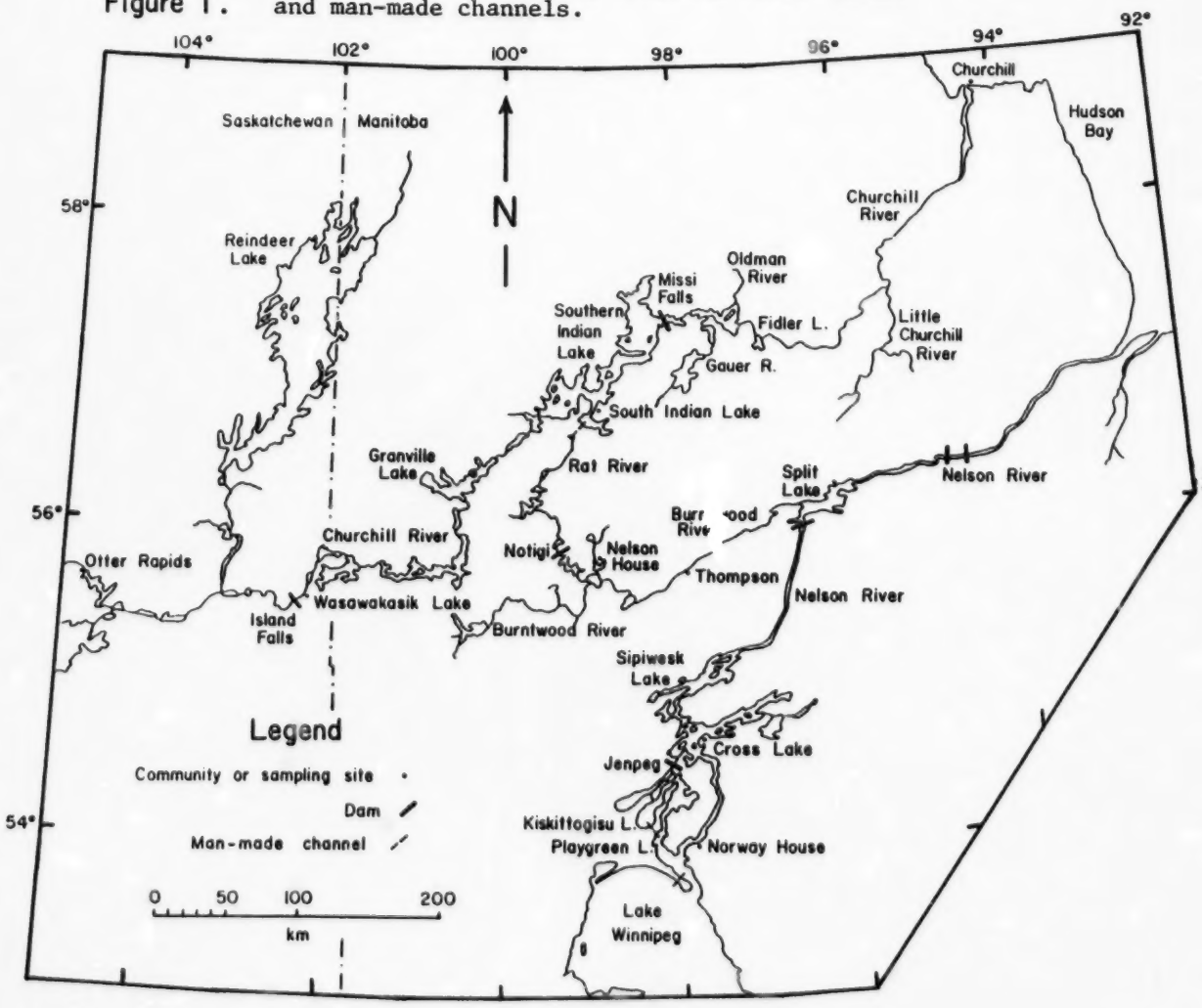
2.0 Study Area

Approximately seventy-five percent of the Churchill River flow in northern Manitoba was diverted southward to increase the hydroelectric generating potential of the Nelson River (Newbury et al. 1984). A control dam was built at Missi Falls, the natural outlet of Southern Indian Lake (Figure 1), and by mid-1976 the lake's level was raised to about 3 m above the long-term mean. A channel was excavated between South Bay, Southern Indian Lake, and the headwaters of the Rat River, in the Nelson River basin. The diverted flow enters the Burntwood River system at Threepoint Lake, and enters the Nelson River at Split Lake. Flow in the Burntwood River increased by about 9 times after the diversion (Bodaly et al. 1984a).

The Nelson River above Split Lake is regulated by various control dams, dykes, and channels. Lake Winnipeg levels are controlled for winter storage at Jenpeg generating station (Figure 1). The control structure at Jenpeg was completed in late 1975. Control channels include 2 Mile Channel between Lake Winnipeg and Playgreen Lake, and 8 Mile Channel between Playgreen Lake and Kiskittogisu Lake. These channels were opened in mid-1976 and the fall of 1975, respectively.

The lakes and rivers of the Churchill, Rat, and Burntwood river systems flow through Precambrian Canadian Shield overlain by glacio-lacustrine deposits. The lakes are usually riverine, relatively shallow, and turbid. High turbidity in the lakes is a result of lake morphology, strong winds, and the fine-grained shore and bottom sediments (Bodaly et al. 1984a). The lakes are generally

Figure 1. The field area, showing sampling sites, dams, and man-made channels.



isothermal during the ice-free season (about 5 months) and have oxygen levels near saturation (Bodaly et al. 1984a). Climate is continental subarctic and vegetation is boreal. The Nelson River system differs from the Churchill, Rat, and Burntwood systems because it drains a large prairie sedimentary area before it enters the Canadian Shield. As a consequence, its total ion concentration and suspended sediments are higher (Bodaly et al. 1984a).

More detail on hydroelectric development of the Churchill and Nelson rivers can be found in Bodaly et al. (1984a), Newbury et al. (1984), and the LWCNR (1975). Further description of the lakes and geology is found in Bodaly et al. (1984a) and Newbury et al. (1984).

3.0 Methods

3.1 Rationale

Water chemistry changes associated with hydroelectric development along the rivers were assessed by comparing data from before and after mid-1976, when the Churchill River diversion occurred. The mid-1976 date was also considered an acceptable approximation for Lake Winnipeg regulation because projects on the upper Nelson River became operational between the fall of 1975 and mid-1976. Choosing one date for data comparison allowed easier, direct comparison of changes at the different sampling sites. Weather-related background variations were also minimized by choosing one comparison date. The sites will be discussed by regions according to the major influences of hydroelectric development. The regions are the reference sites above Southern Indian Lake, the lower Churchill River (reduced flow), the Rat-Burntwood system and Split Lake (along

the diversion path), and the upper Nelson River (affected by Lake Winnipeg regulation).

3.2 Data validation and statistical analysis

Water chemistry data were collected at various sites between 1972 and 1984 by Manitoba Environment and Workplace Safety and Health. These data were supplemented with Canada Department of Environment and Canada Department of Fisheries and Oceans data for the same sites. Combining data generated by separate agencies may have introduced some error because of differences in collection and laboratory procedures, but it was thought that the additional information would benefit analysis overall.

Twenty parameters were chosen for statistical analysis (see Figure 2). Data from the earlier years of chemical analysis were not used for eight of these parameters because of methods changes (Appendix 1). Methods changes in 1975 excluded iron, copper, and lead from statistical analysis (Appendix 1). Too few data was the usual reason for exclusion from data analysis: at least two year's data from before and after mid-1976 were required for statistical analysis, with at least six reasonably-spaced data per period (i.e. not all winter samples). An exception to these arbitrary criteria was coliform bacteria, where five or more samples from before mid-1976 were accepted. Coliform bacteria were of special interest because of their human health implications.

Data means from before June 30, 1976 were compared with means from after July 1, 1976, using Student's t-test. The null hypothesis tested was that water chemistry did not change in the two periods of comparison. A two-tailed test was used, with a significance of

P <= 0.05 indicating inequality of the means. An NWA STATPAK (1984) t-test program on an IBM personal computer was used. Unequal variances were assumed (Welch's method; NWA STATPAK 1984).

As described previously, care was taken to ensure data compatibility before statistical analysis was done. In addition, occasional data that were obvious outliers (i.e. a misplaced decimal) and could not be verified were discarded. Occasional data reported as less than a detection limit were arbitrarily assigned one-half the detection limit; if there were too many (>20%), the analysis for that parameter was not done. Log (x+1) transformations were applied to coliform bacteria data before statistical analysis because of the very large range of values. Bacterial means given in the text were transformed back, and are essentially geometric means of the original bacteria data.

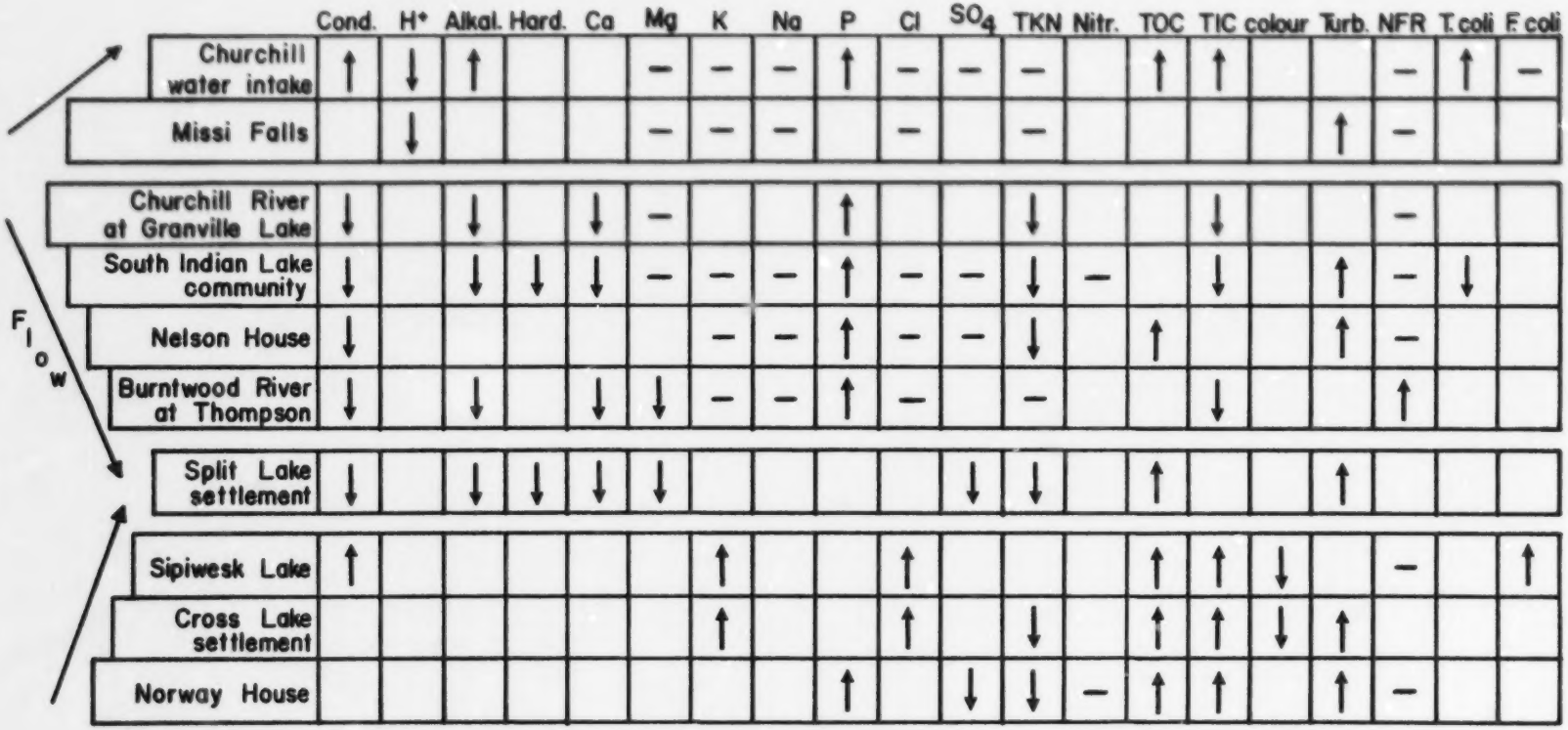
4.0 Results and Dissussion

The results of the comparisons of water chemistry data from before and after mid-1976 are summarized in Figure 2. Significant increases or decreases of twenty parameters at ten sites are shown. The results are presented in more detail in the following sections, but Figure 2 gives an overview of regional trends. For example, conductivity decreased at sites between Granville Lake and Split Lake settlement, whereas an increase or no change in conductivity was found at sites below Missi Falls and on the upper Nelson River.

The difficulty in interpreting the many changes in water chemistry lies in separating changes related to the Churchill River diversion and Lake Winnipeg regulation projects from natural, temporal background variation. The analysis is further complicated by changes

Figure 2.

Summary of changes in water chemistry for sites on the Churchill, Rat, Burntwood, and Nelson rivers. A t-test was used to compare data from before June 30, 1976, with data from after July 1, 1976. Cond. = conductivity, H^+ = hydrogen ions, Alkal. = alkalinity, Hard. = hardness, Ca = calcium, Mg = magnesium, K = potassium, Na = sodium, P = phosphorus, Cl = chloride, SO_4 = sulphate, TKN = total Kjeldahl nitrogen, Nitr. = nitrate-nitrite, TOC = total organic carbon, TIC = total inorganic carbon, colour = colour in colour units, Turb. = turbidity, NFR = non-filterable residue, T. coli = total coliform bacteria, and F. coli = fecal coliform bacteria.



↑ = increase, ↓ = decrease, and an empty box = no change; $P \leq 0.05$.

— = insufficient data or too many data less than the detection limit.

caused by man upriver of Southern Indian Lake, by spurious changes resulting from the statistical analysis used, and by apparent changes resulting from changes in laboratory methods. In addition, although it can be stated with a certain probability that a particular parameter increased or decreased after mid-1976, it is impossible to calculate the probability that a given change was caused by the hydroelectric projects. This is because, unlike a properly run experiment to which statistical analysis can be used to infer cause and effect, there was no treatment (project) replication, interspersion, or randomization, and there were no controls (Hurlbert 1984). However, when reasonable chemical, biological, or hydrological explanations for changes in water chemistry were available it was possible to use common sense to decide whether or not certain changes were caused by hydroelectric development of the rivers. This was especially possible when predictions made by the LWCNR (1975) could be tested.

4.1 Reference site

The Churchill River at Granville Lake, above Southern Indian Lake, was considered a reference site because it was unaffected by the diversion. However, at Granville Lake there were statistically significant decreases in conductivity, alkalinity, calcium, total inorganic carbon, and total Kjeldahl nitrogen, and a statistically significant increase in total phosphorus (Table 1; Figure 3). Similar changes in water chemistry were observed at Otter Rapids and Wasawakasik Lake, located on the Churchill River upriver of Granville Lake (Appendix 2). In addition, there were statistically significant decreases in concentrations of potassium, sodium, chloride, and

sulphate at Wasawakasik Lake. The number of data from each time period used in the Student's t-test comparisons, plus the standard deviation of the means, are given in Appendix 3 for these and all other sites discussed.

Water chemistry changes in the Churchill River above Southern Indian Lake were either caused by different patterns of release from Reindeer Lake reservoir or were a result of variation in a natural phenomenon such as precipitation. Statistically significant decreases in concentrations of potassium, sodium, chloride, sulphate, total inorganic carbon, and an increase in total phosphorus were observed at Wasawakasik Lake, but none of these parameters changed further upriver at Otter Rapids (Appendix 2). This implies an influence on water chemistry somewhere between the two sites, and probably resulted from variations in the discharge from Reindeer Lake reservoir above Island Falls generating station (Figure 1). Annual discharge from Reindeer Lake has varied between 25 and 55% of the discharge at Island Falls (Water Survey of Canada, Inland Waters Directorate, 1972 to 1978 data). At Granville Lake the increase in total phosphorus and decreases in total inorganic carbon and calcium can be explained in the same manner. In contrast, conductivity and alkalinity decreased at Granville Lake, Wasawakasik Lake, and Otter Rapids (Table 1, Appendix 2), which suggests that these changes were mostly due to natural variation. Increased precipitation resulting in above-average Churchill River discharge in 1974 to 1977 (Newbury et al. 1984) could be responsible.

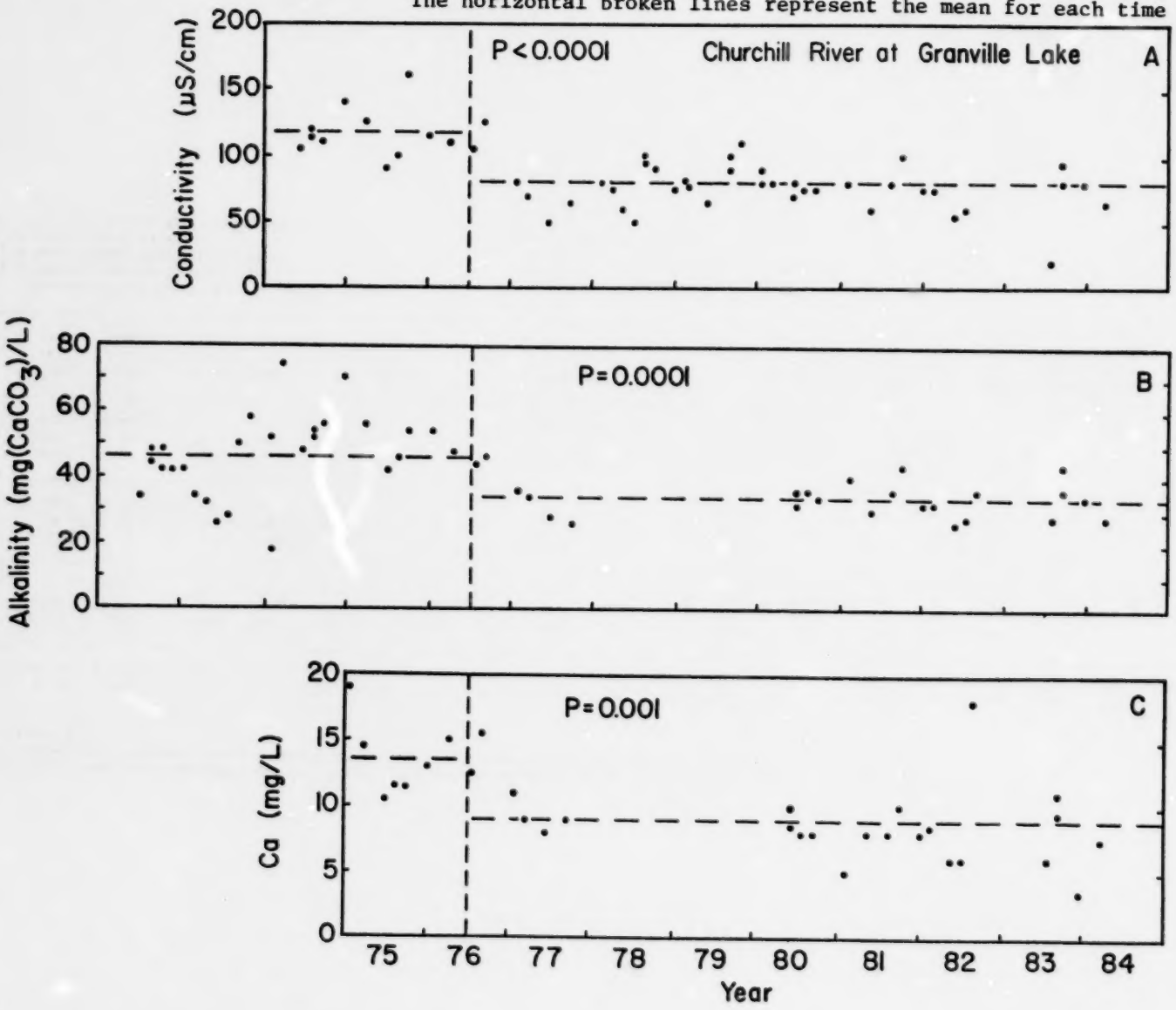
Whatever their cause, changes in Churchill River water chemistry at Granville Lake, and therefore along the Churchill River diversion path, make interpretation of the data for conductivity,

Table 1. Comparison of data from before and after mid-1976 for the Churchill River at Granville Lake, Southern Indian Lake near South Indian Lake community, Footprint Lake near Nelson House, and the Burntwood River at Thompson. Parameter abbreviations are defined in Figure 2.

Location		Cond. µS/cm	H^+ x10^{-8}M/L	Alkal. mg/L	Hard. mg/L	Ca mg/L	Mg mg/L	K mg/L	Na mg/L	Total P µg/L	Cl mg/L	SO_4 mg/L	TKN mg/L	NO_3-NO_2 mg/L	TOC mg/L	TIC mg/L	Colour units	Turb. NTU	NFR mg/L	T.Coli MPN/100 mL	F. Coli MPN/100 mL
Churchill River at Granville Lake	P	<.0001	.148	.0001	.282	.001		.328	.317	<.0001	.057	.178	.026	.846	.080	.022	.427	.472		.162	.973
	$\bar{x}_1$	118	2.84	46	46	13.5	-	1.3	3.3	15	1.3	4	0.6	0.06	8	9	12	4.3	-	8	0.4
	$\bar{x}_2$	78	3.52	34	41	8.9		1.2	3.0	22	1.0	6	0.4	0.05	10	8	16	4.9		3	0.4
South Indian Lake Community	P	<.0001	.738	<.0001	<.0001	.003				<.0001			.038		.350	<.0001	.981	.001		.040	.103
	$\bar{x}_1$	128	1.85	58	58	16.0	a	a	a	17	a	a	0.6	a	9	13	11	3.7	a	10	1.0
	$\bar{x}_2$	84	1.77	40	37	10.6				28			0.3		10	8	11	8.0		3	0.3
Nelson House	P	.003	.425	.178	.421	.237	.243			<.0001			<.0001	.563	.0003	.808	.054	.040		.212	.623
	$\bar{x}_1$	165	2.18	76	80	23.2	6	a	a	25	a	a	0.7	0.09	12	16	27	2.7	a	3	0.1
	$\bar{x}_2$	142	2.47	71	76	20.9	5			39			0.5	0.08	14	16	22	4.7		2	0.1
Burntwood River at Thompson	P	<.0001	.286	<.0001	.086	.007	<.0001			<.0001		.056		.731	.516	.032	.182	.209	.002	.879	.408
	$\bar{x}_1$	147	1.87	68	71	21.3	6	a	a	35	a	4	-	0.11	13.5	14.3	50	21.8	11.4	22	1.5
	$\bar{x}_2$	116	1.65	58	68	17.9	5			58		5		0.12	13.0	13.0	41	18.6	19.7	19	3.2

P = probability of equality of $\bar{x}_1$ and $\bar{x}_2$, t-test.
$\bar{x}_1$ = mean of data to June 30, 1976.
$\bar{x}_2$ = mean of data from July 1, 1976.
- = insufficient data.
a = too many data < detection limit.

Figure 3. Chemical changes in the Churchill River at Granville Lake. For Figures 3 to 12 the vertical broken line represents July 1, 1976. The horizontal broken lines represent the mean for each time period.



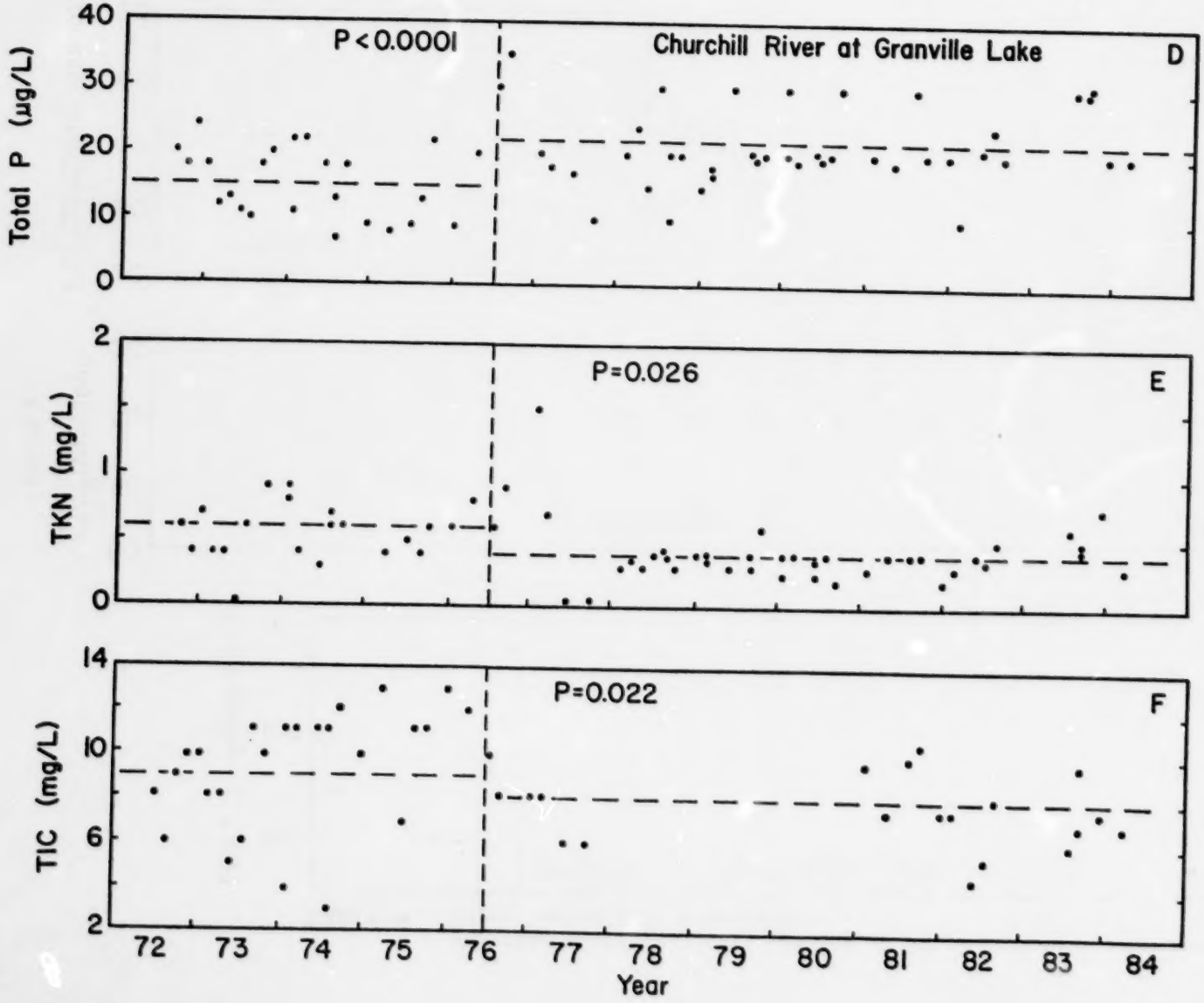
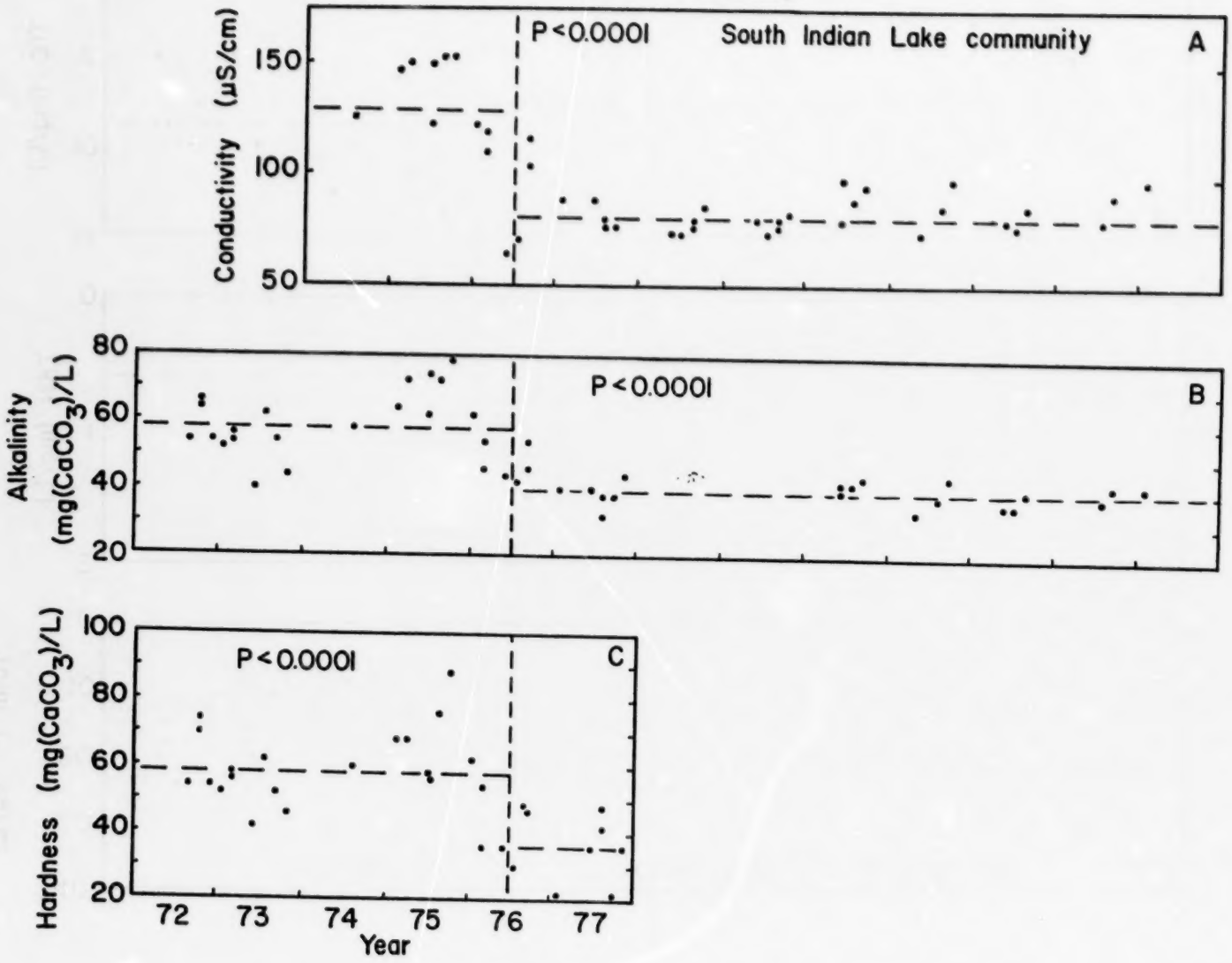

Churchill River at Granville Lake
P < 0.0001
D
Total P (µg/L)
40
30
20
10
0
P=0.026
E
TKN (mg/L)
2
1
0
P=0.022
F
TIC (mg/L)
14
10
6
2
72
73
74
75
76
77
78
79
80
81
82
83
84
Year

Figure 4. Selected water chemistry changes in Southern Indian Lake near South Indian Lake community.



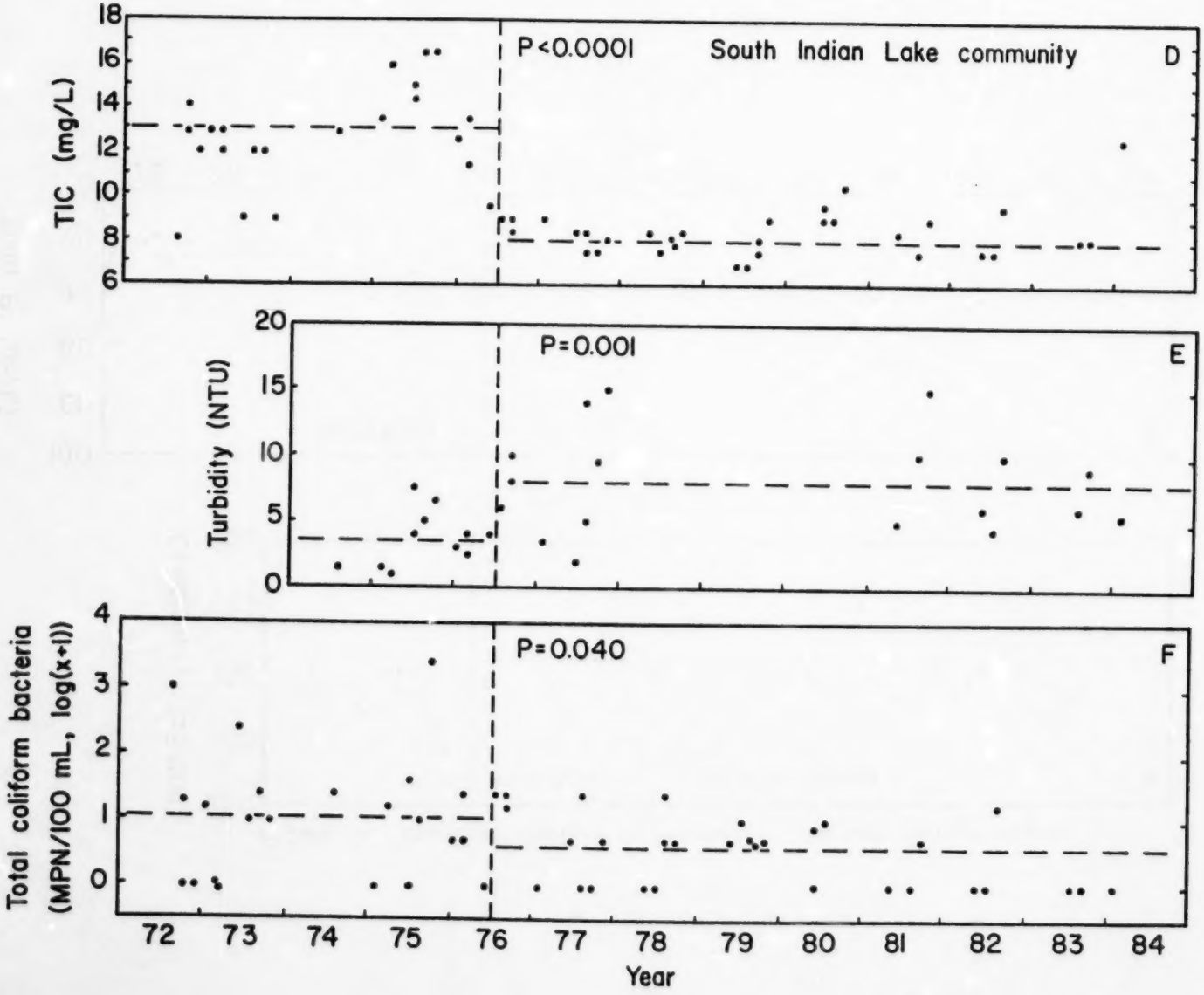
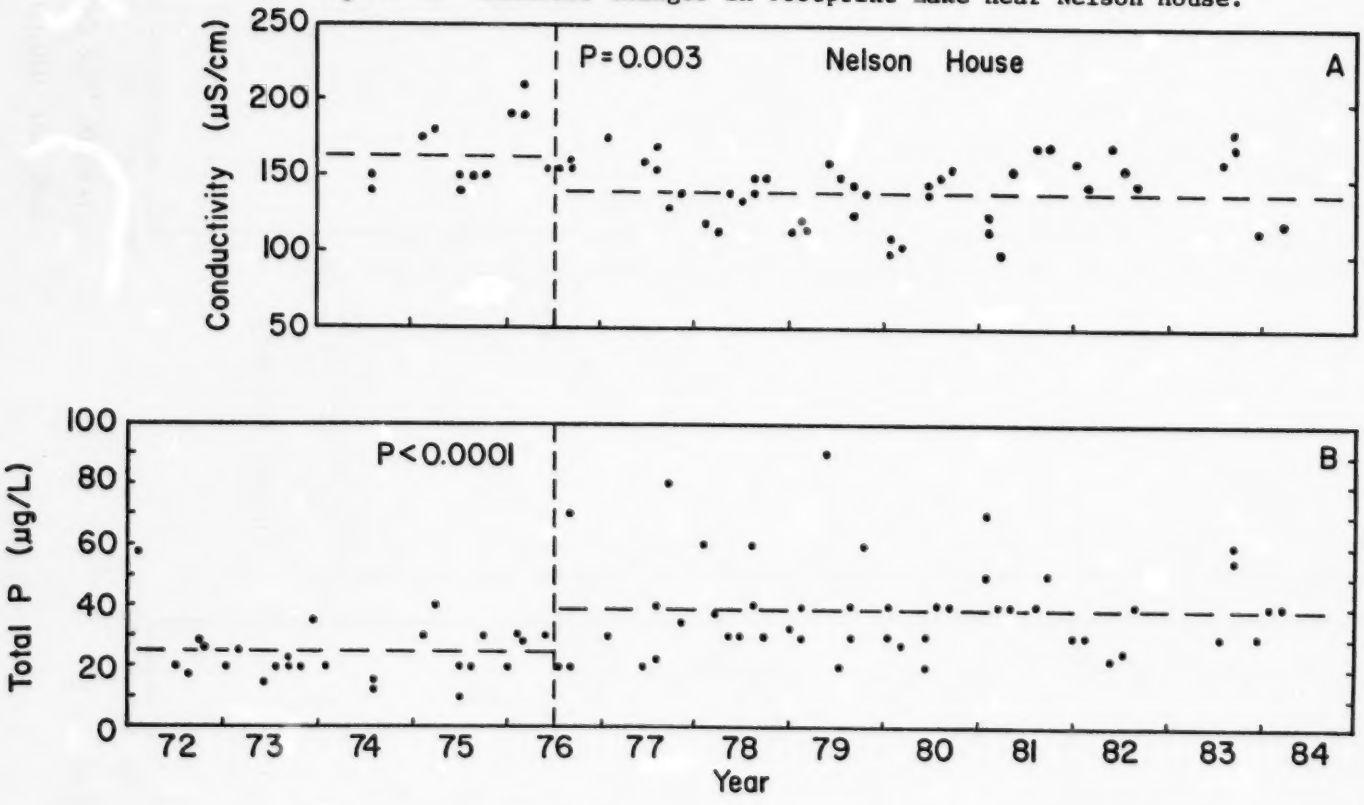

P<0.0001
South Indian Lake community
D
TIC (mg/L)
18
16
14
12
10
8
6
P=0.001
E
Turbidity (NTU)
20
15
10
5
0
P=0.040
F
Total coliform bacteria
(MPN/100 mL, log(x+1))
4
3
2
1
0
72
73
74
75
76
77
78
79
80
81
82
83
84
Year

Figure 5. Chemical changes in Footprint Lake near Nelson House.



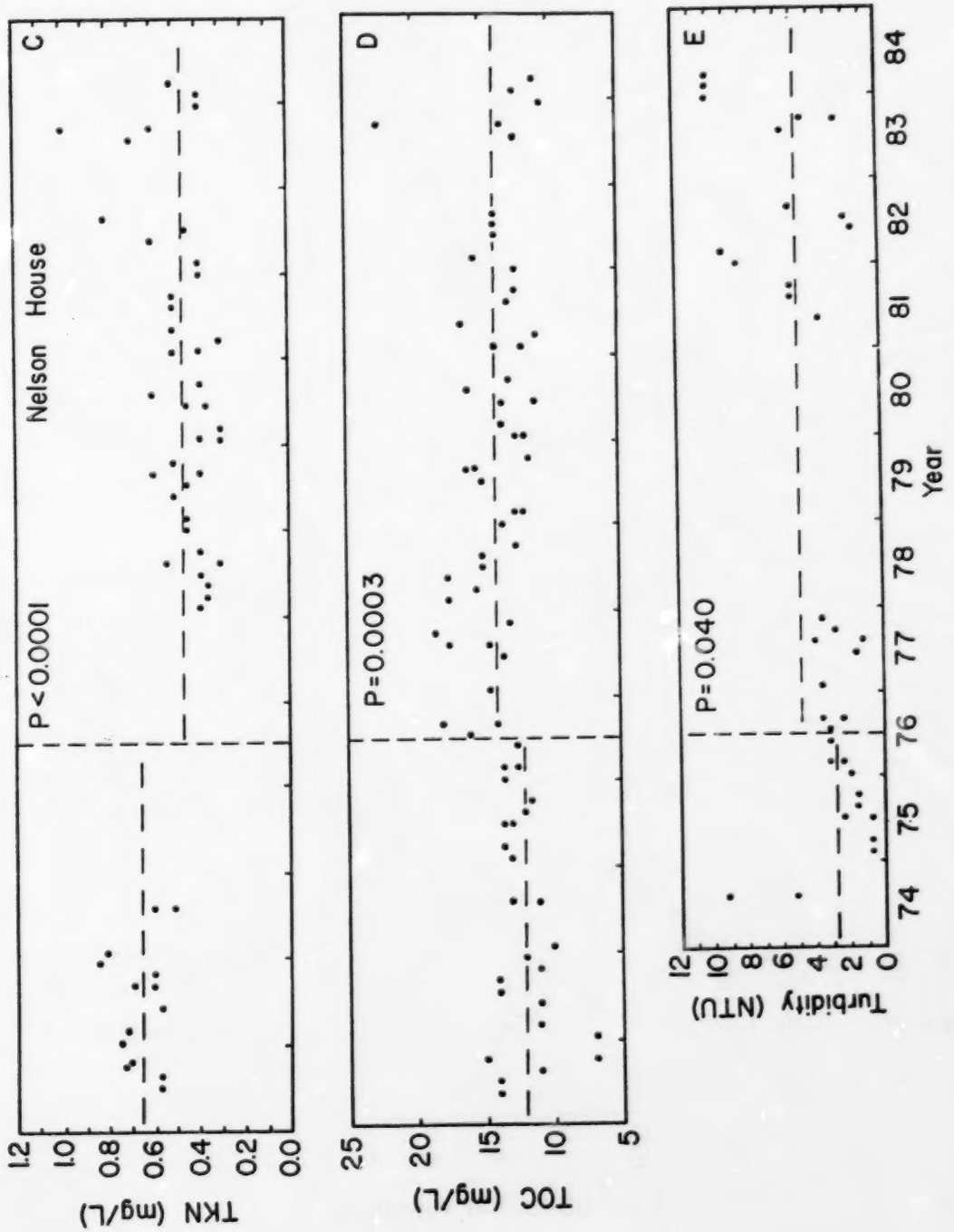
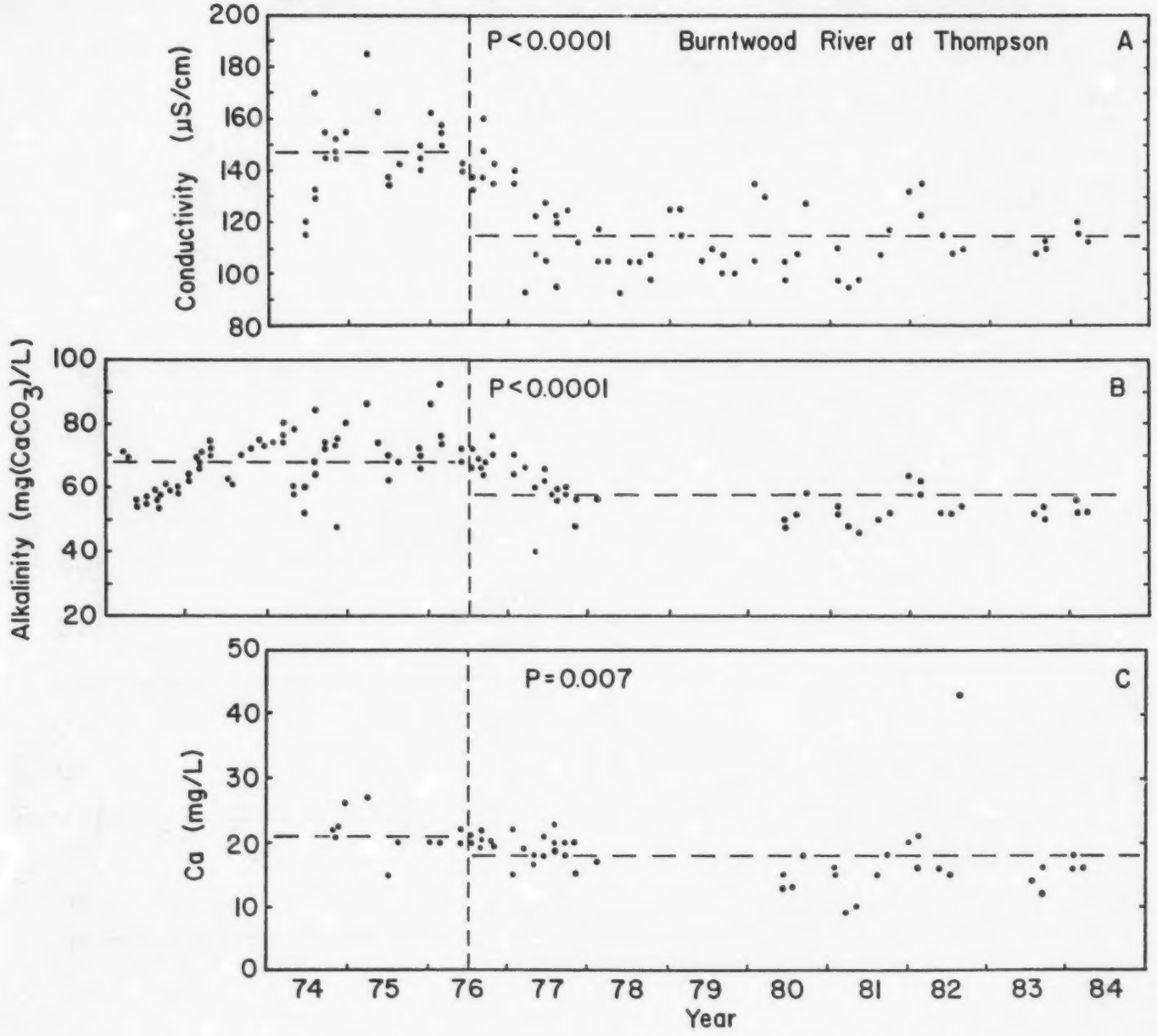
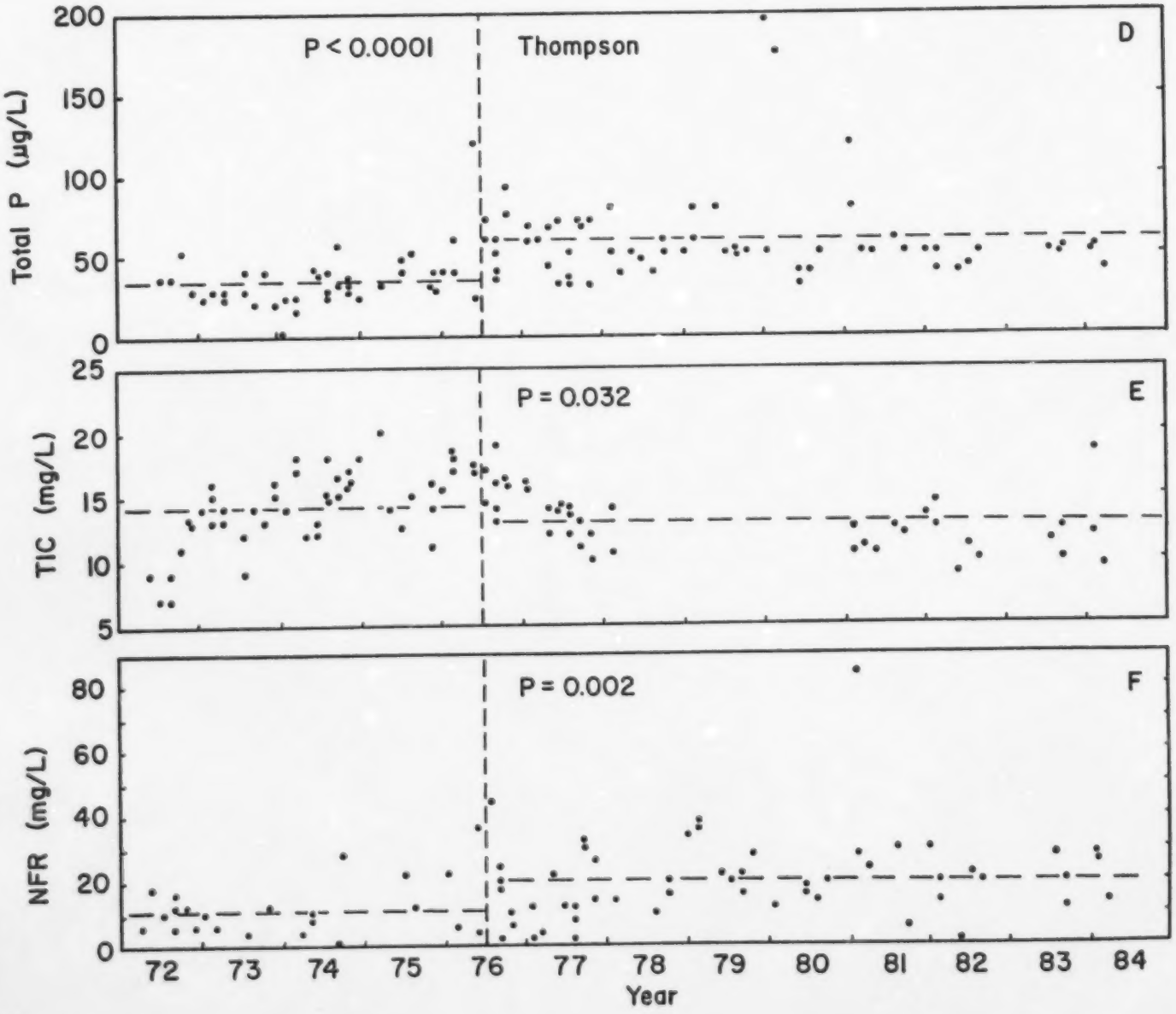

C
Nelson House
P<0.0001
TKN (mg/L)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
D
P=0.0003
TOC (mg/L)
5
10
15
20
25
E
P=0.040
Turbidity (NTU)
0
2
4
6
8
10
12
74
75
76
77
78
79
80
81
82
83
84
Year

Figure 6. Chemical changes in the Burntwood River at Thompson.




P < 0.0001
Thompson
D
Total P (µg/L)
200
150
100
50
0
P = 0.032
E
TIC (mg/L)
25
20
15
10
5
P = 0.002
F
NFR (mg/L)
80
60
40
20
0
72
73
74
75
76
77
78
79
80
81
82
83
84
Year

alkalinity, calcium, total phosphorus, and total inorganic carbon difficult (Figure 2). Interpretation of total Kjeldahl nitrogen data was also difficult because this parameter decreased significantly at all sites except Sipiwesk Lake, and even there a decrease was indicated (from 0.6 to 0.4 mg/L, P = 0.090; Table 2). Analytical bias or a natural decreasing trend over all the rivers could have caused the apparent decreases in total Kjeldahl nitrogen. As a consequence, total Kjeldahl nitrogen results will not be discussed further.

4.2 Churchill River diversion route

4.2.1 South Indian Lake community

Water chemistry in Southern Indian Lake near the community of South Indian Lake changed in a similar manner as at Granville Lake. However, there were also statistically significant decreases in hardness and in total coliform bacteria, and an increase in turbidity (Table 1, Figure 4). Changes in calcium, total phosphorus, and total Kjeldahl nitrogen differed mainly in magnitude from those at Granville Lake so are not presented in Figure 4.

Most of the water chemistry changes near South Indian Lake settlement were a result of the increased flow of Churchill River water past a previously sheltered section of Southern Indian Lake. Before the diversion, conductivity, alkalinity, hardness, calcium, and total inorganic carbon were all higher at South Indian Lake than at Granville Lake or the Churchill River at Missi Falls (Tables 1 and 3). The residence time of South Bay (just south of South Indian Lake community) was calculated to be four years (Bodaly et al. 1984a). After the diversion, water chemistry near South Indian Lake was very similar to the Churchill River at Granville Lake, as predicted by the LWCNR (1975). South Bay residence time decreased to 11 days (Bodaly

et al. 1984a). Mean total coliform bacteria decreased at South Indian Lake because of increased flow past the community. Fecal coliform counts also decreased, but the decrease was not statistically significant (Table 1). The LWCNR (1975) predicted that the increased flow past South Indian Lake community would reduce local lakeshore contamination.

The increase in turbidity at South Indian Lake (Table 1) was caused by flooding of Southern Indian Lake and the subsequent erosion of fine-grained tills and lacustrine soils in permafrost (Bodaly et al. 1984a; Newbury and McCullough 1984). Flooding of Southern Indian Lake was expected to increase lake phosphorus concentrations because of additions of nutrients from newly flooded lands (LWCNR 1975). This prediction could not be rigorously tested using South Indian Lake data because of the increases in total phosphorus in the Churchill River upriver of the diversion. However, the percent increase in pre- and post-diversion phosphorus at South Indian Lake was 65%, compared to 47% at Granville Lake. The magnitude of the increase suggests some phosphorus release from flooded land. The predicted increase in nutrients was not expected to increase biological activity in Southern Indian Lake because the Churchill River was already nutrient-rich, and increased turbidity was expected to reduce any positive effects of the nutrients (LWCNR 1975).

4.2.2 Nelson House

Water chemistry near the community of Nelson House was relatively stable during the diversion (Figure 2), a consequence of its location off the main flow of the diversion. Conductivity decreased from 165 to 142 µS/cm ($P = 0.003$), probably because of

diverted, softer Churchill River water (Table 1, Figure 5). Water levels at Nelson House increased by about 3.6 m after the diversion (Bodaly et al. 1984b). Flooding was likely responsible for the observed increases in total organic carbon and turbidity (Table 1). The increase in total phosphorus was difficult to interpret because of the increases in total phosphorus seen at sites above the diversion. However, the magnitude of the increase (from 25 to 39 µg/L) suggests that release of phosphorus from newly flooded land was responsible for some of the increase.

4.2.3 Burntwood River at Thompson

The Churchill River diversion resulted in increased river flow past Thompson. Flow in the Burntwood River is now about nine times the historical mean flow (Bodaly et al. 1984a). The softer Churchill River water responsible for the flow increase caused reductions in conductivity, alkalinity, calcium, magnesium, and total inorganic carbon at Thompson. These values are now closer to those of the Churchill River at Granville Lake (Table 1, Figure 6; the change in magnesium was similar to the change in calcium so is not presented in Figure 6). The changes in these parameters were similar to the effects seen at South Indian Lake settlement. Total phosphorus concentrations increased at Thompson. The magnitude of the increase suggests that some of the increase was due to nutrient release from flooded land upriver. Non-filterable residues increased from 11.4 to 19.7 mg/L ($P=0.002$). Turbidity in the historically turbid Burntwood River did not increase, which is contradictory to the non-filterable residue results. Perhaps the contradiction is a result of two opposing influences: increased flow causing increased riverbed

erosion, and increased flow bringing less turbid water past Thompson.

Guilbault et al. (1979) also found a decrease in calcium concentration and an increase in phosphorus in a similar analysis of water chemistry data from the Burntwood River at Thompson. In addition, they found significant increases in potassium (from 1.0 to 1.5 mg/L, $P \simeq < 0.001$) and aluminum (from 0.04 to 0.54 mg/L, $P \simeq < 0.001$). Potassium data from Thompson were not analyzed in this study because too many data were below the detection limit, and aluminum data were not analyzed because of insufficient data. Guilbault et al. (1979) could not explain the increase in potassium, but thought that the additional aluminum and phosphorus came from leached and eroded soil. However, their observed increase in aluminum concentration may have been an artifact of a change in methods from dissolved to extractable aluminum in 1975.

4.3 Nelson River sites

4.3.1 Split Lake settlement

Split Lake is located at the junction of the Burntwood and Nelson rivers, and can be affected by changes in either river system. Before the diversion, water chemistry at Split Lake settlement was dominated by the upper Nelson, with higher conductivity, alkalinity, hardness, and major ions than the Burntwood River (cf. Tables 1 and 2). After the diversion the increased flow of diverted, softer water down the Burntwood River caused statistically significant decreases in conductivity, alkalinity, hardness, calcium, magnesium, and sulphate (Table 2, Figure 7). Most of the changes were also observed between Granville Lake and Thompson (Figure 2). The change in magnesium was similar to the change in calcium so is not presented in Figure 7.

Split Lake flow increased about 34 percent because of the diversion. Mean conductivity decreased from 290 to 235 µS/cm, even though conductivity increased significantly at Sipiwesk Lake, upriver from Split Lake on the Nelson River (Table 2). Hardness had been predicted to drop from 125 to 100 mg ($CaCO_3$)/L (LWCNR 1975); the actual decrease was from 121 to 106 mg ($CaCO_3$)/L. The decrease in calcium concentration was predicted to be from 30 to 27 mg/L (LWCNR 1975). The actual decrease was from 29 to 25 mg/L (Table 2). A change in total inorganic carbon was not observed at Split Lake. This likely occurred because the increased Burntwood River flow of water of lower total inorganic carbon countered the increased carbon load flowing down the Nelson (Table 2). Total organic carbon increased from 10 to 13 mg/L at Split Lake, following the trend of the upper Nelson River (Table 2, Figure 2). Total organic carbon data are not presented in Figure 7 because the pattern was similar to other total organic carbon changes on the upper Nelson.

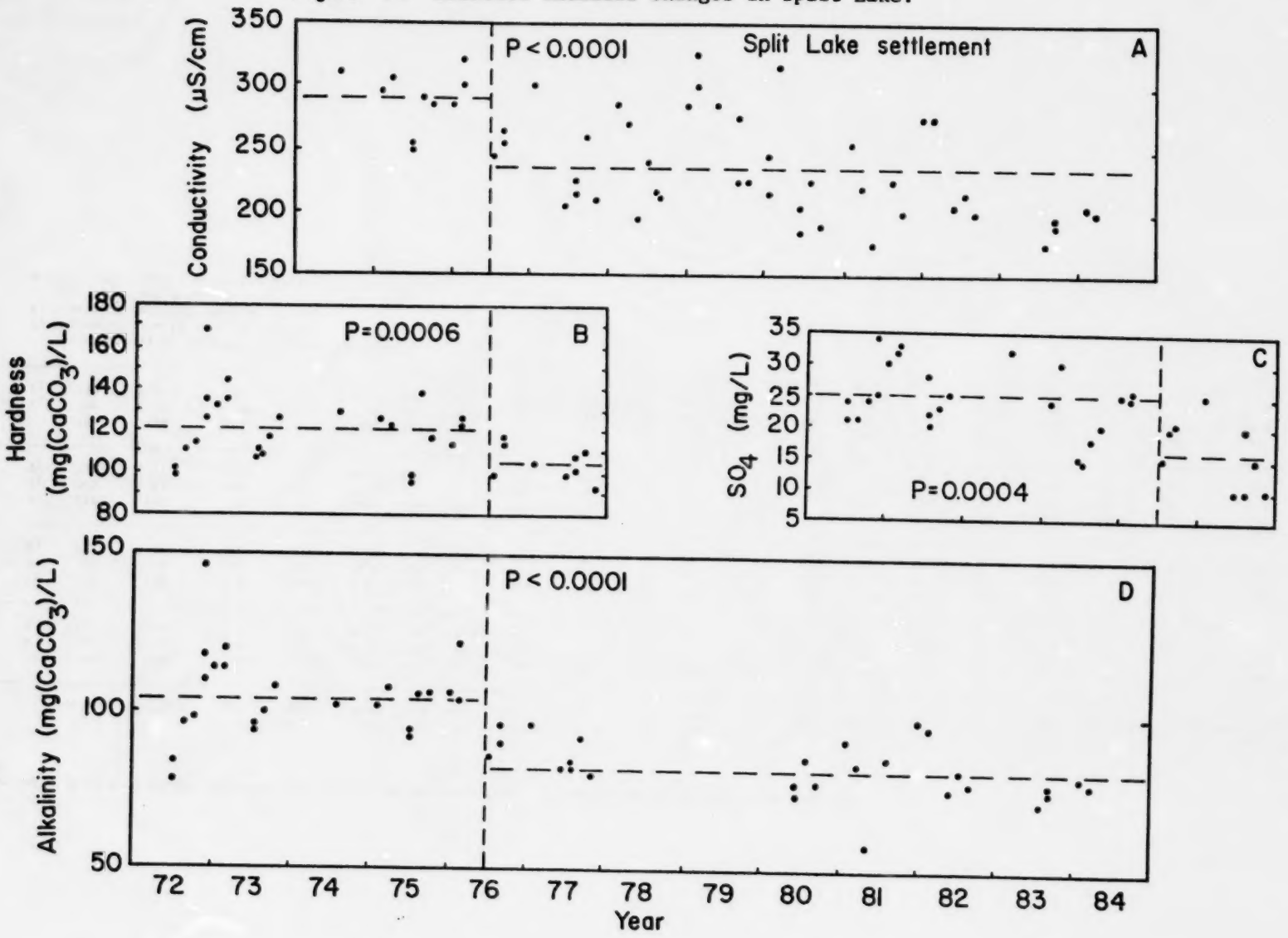
Turbidity at Split Lake increased after mid-1976, likely because of increased flow of turbid water along the Burntwood River (cf. Thompson data, Table 1, with Split Lake data, Table 2). However, high turbidities were recorded at all four Nelson River sites in 1972 (maximum and mean turbidities for Split Lake were 35 and 24 JTU, respectively). These data were excluded from the statistical analysis because of methods changes (Appendix 1), but they suggest that turbidity changes in the upper Nelson can be erratic and perhaps cyclic. The increase in mean turbidity from 7.2 to 13.6 NTU after mid-1976 (Table 2), which reflects high Burntwood River turbidity (i.e. at Thompson) not upper Nelson River turbidities (Table 2), plus

Table 2. Comparison of data from before and after mid-1976 for Nelson River sites. Parameter abbreviations are defined in Figure 2.

Location		Cond. µS/cm	H^+ x10^{-8}H/L	Alkal. mg/L	Hard. mg/L	Ca mg/L	Mg mg/L	K mg/L	Na mg/L	Total P µg/L	Cl mg/L	SO_4 mg/L	TKN mg/L	NO_3-No_2 mg/L	TOC mg/L	TIC mg/L	Colour units	Turb. NTU	NFR mg/L	T.Coli MPN/100 mL	F. Coli MPN/100 mL
Split Lake settlement	P	<.0001	.228	<.0001	.0006	.007	.003	.875	.074	.480	.172	.0004	.002	.553	<.0001	.211	.153	.001	.716	.180	.242
	$\bar{x}_1$	290	1.07	104	121	29.2	11	2.4	15	57	16	25	0.6	0.08	10	21	21	7.2	11	7	0.8
	$\bar{x}_2$	235	0.94	83	106	25.2	9	2.3	13	41	14	16	0.4	0.07	13	19	18	13.6	11	12	1.6
Sipiwesk Lake	P	.009	.178	.304	.465	.062	.115	.010	.167	.765	.005	.839	.090	.575	<.0001	.001	.048	.868		.573	.025
	$\bar{x}_1$	302	1.00	103	120	29.0	11	2.5	17	33	18	26	0.6	0.06	9.4	20.6	15	8.3	a	1	0.0
	$\bar{x}_2$	323	0.86	106	124	31.9	12	3.0	19	32	21	26	0.4	0.07	12.8	24.3	9	8.6		2	0.2
Cross Lake Settlement	P	.052	.196	.493	.759	.266	.257	.027	.087	.986	.001	.575	.0001	.142	<.0001	.0002	.012	.028	.526	.082	.594
	$\bar{x}_1$	303	1.61	101	120	29.2	11	2.6	16	35	17	28	0.6	0.13	10	20	16	5.7	10	15	0.5
	$\bar{x}_2$	320	1.17	103	119	30.5	12	3.2	19	35	23	27	0.5	0.06	14	24	11	8.4	8	6	0.7
Norway House	P	.704	.488	.493	.112	.830	.806	.351	.681	.014	.204	.046	.005		.0004	.004	.778	.023		.240	.851
	$\bar{x}_1$	296	1.13	99	114	27.8	11	2.3	16	25	16	25	0.7	a	11	19	16	5.3	a	14	0.9
	$\bar{x}_2$	292	1.03	96	106	28.3	11	2.5	15	33	18	21	0.5		15	22	15	7.2		9	1.0

P = probability of equality of $\bar{x}_1$ and $\bar{x}_2$, t-test.
$\bar{x}_1$ = mean of data to June 30, 1976.
$\bar{x}_2$ = mean of data from July 1, 1976.
- = insufficient data.
a = too many data < detection limit.

Figure 7. Selected chemical changes in Split Lake.



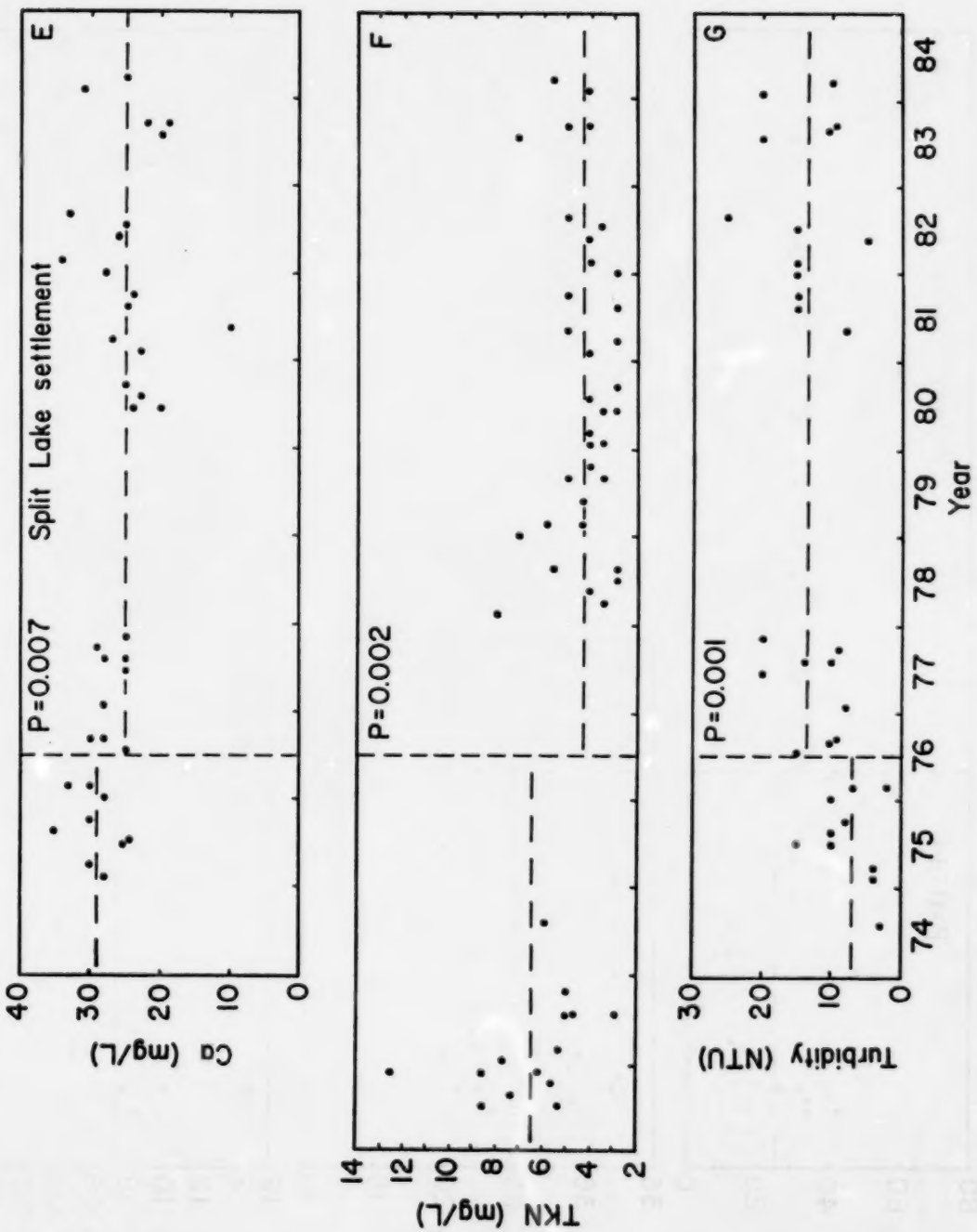
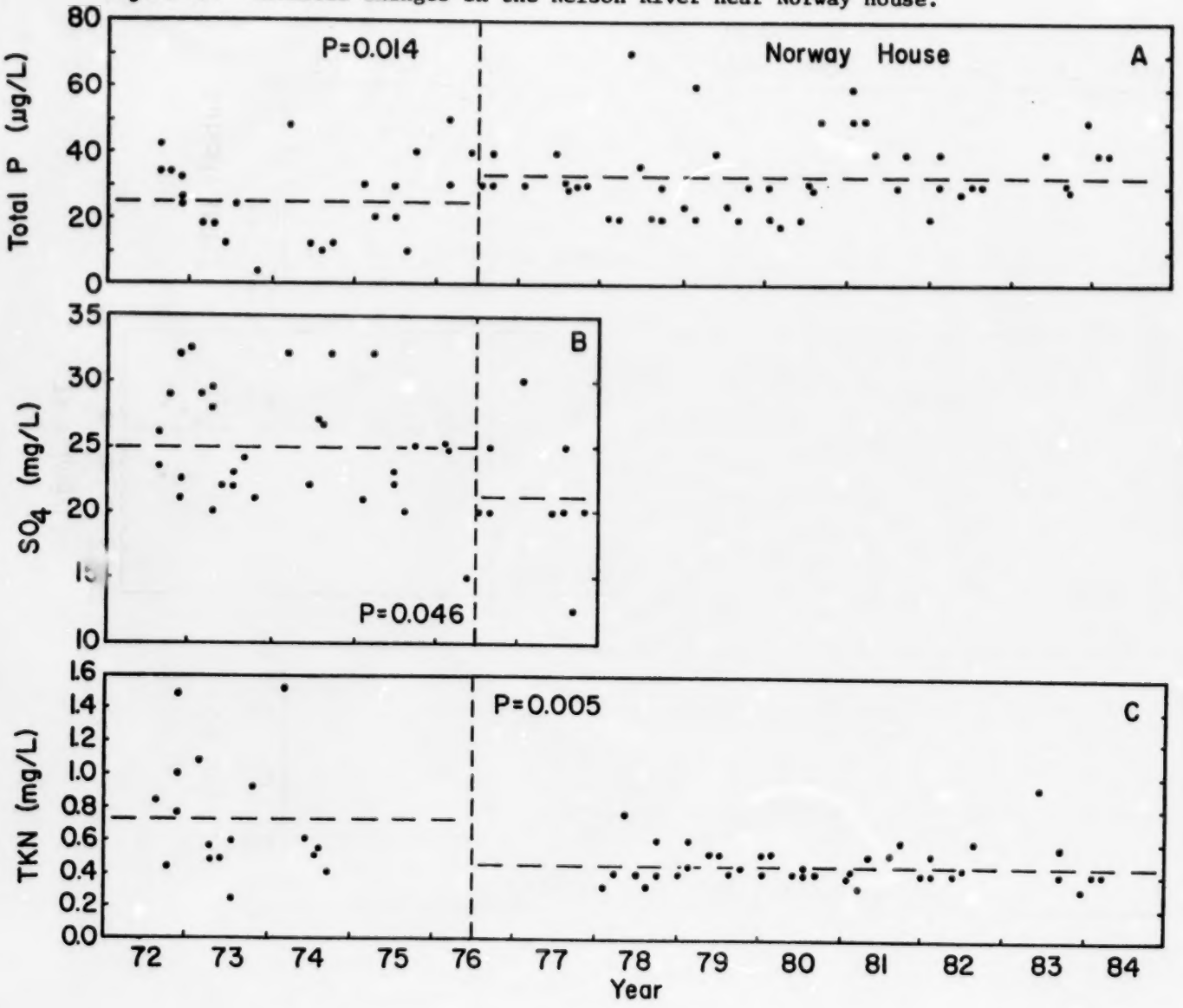

E
Split Lake settlement
P=0.007
Ca (mg/L)
0
10
20
30
40
F
P=0.002
TKN (mg/L)
2
4
6
8
10
12
14
G
P=0.001
Turbidity (NTU)
0
10
20
30
74
75
76
77
78
79
80
81
82
83
84
Year

Figure 8. Chemical changes in the Nelson River near Norway House.



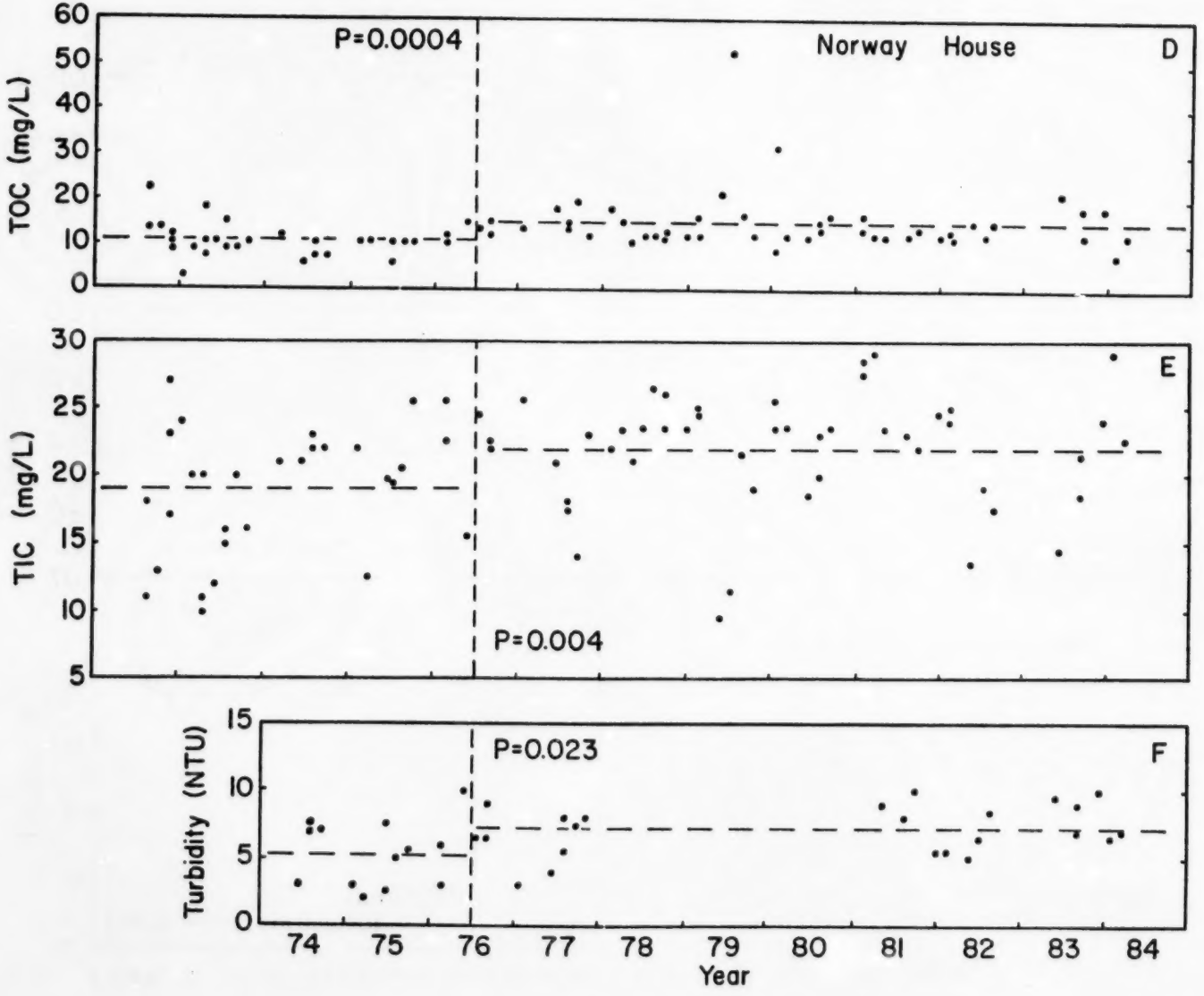
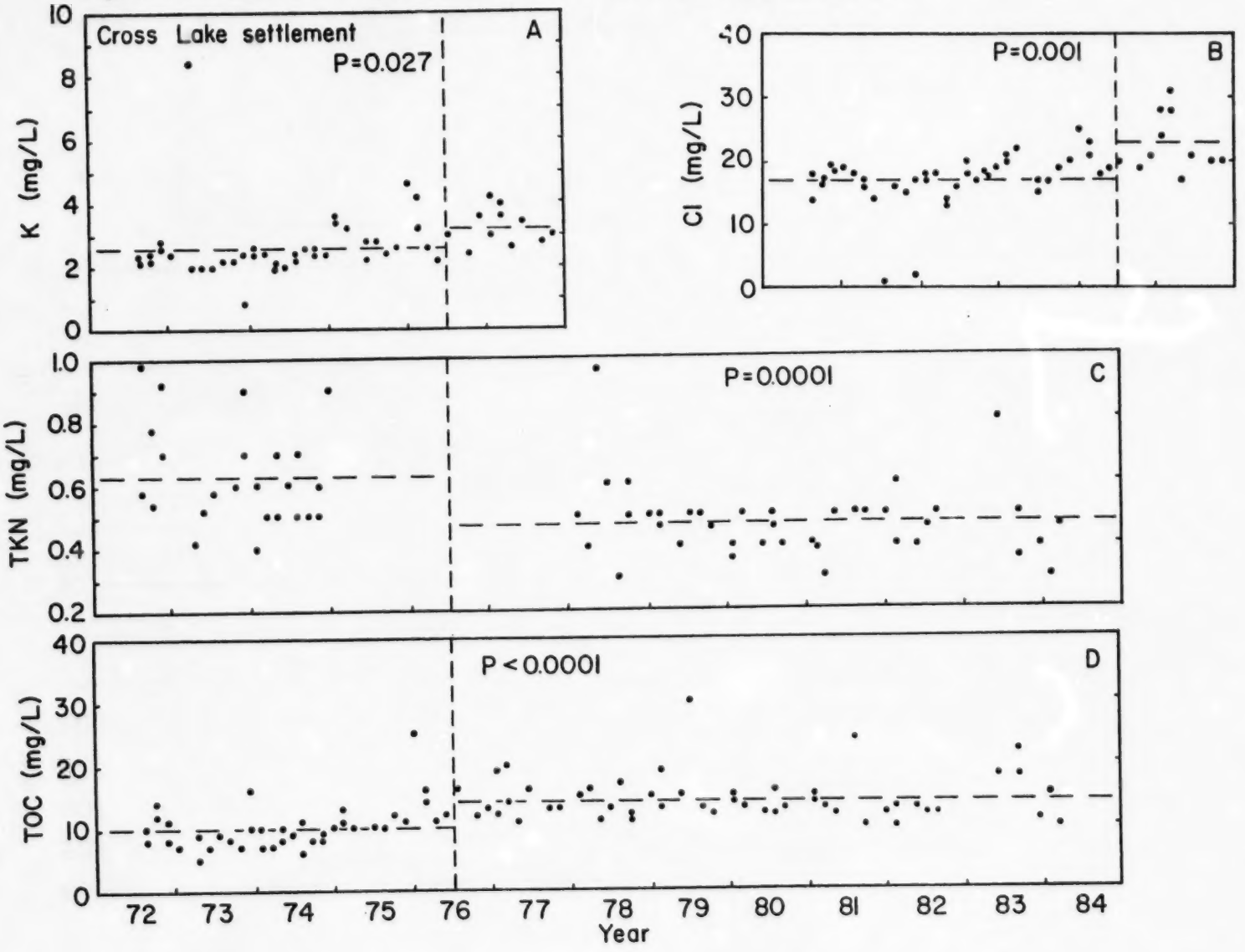

P=0.0004
Norway House
D
TOC (mg/L)
60
50
40
30
20
10
0
E
TIC (mg/L)
30
25
20
15
10
5
P=0.004
P=0.023
F
Turbidity (NTU)
15
10
5
0
74
75
76
77
78
79
80
81
82
83
84
Year

Figure 9. Chemical changes in Cross Lake near Cross Lake settlement.



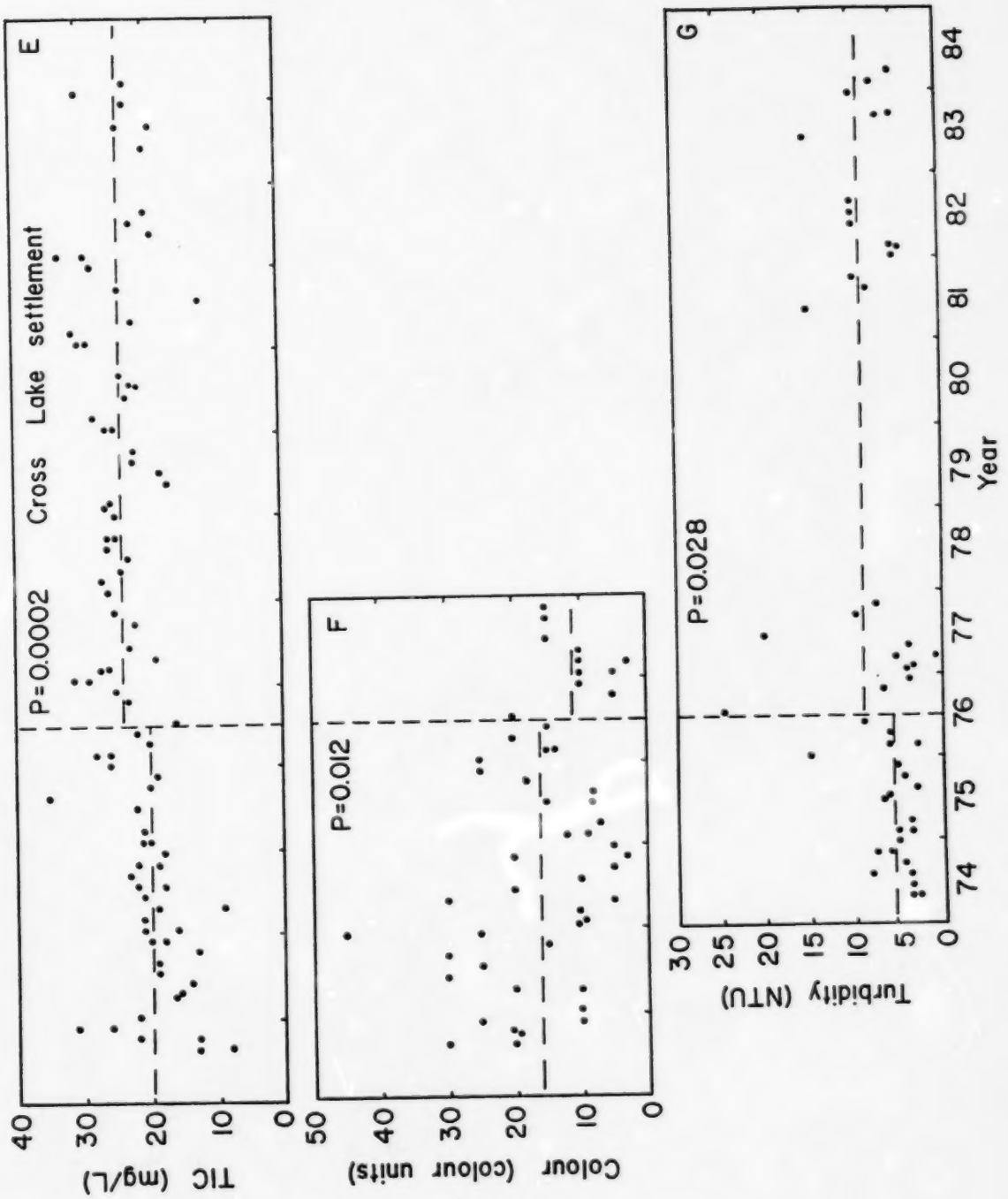
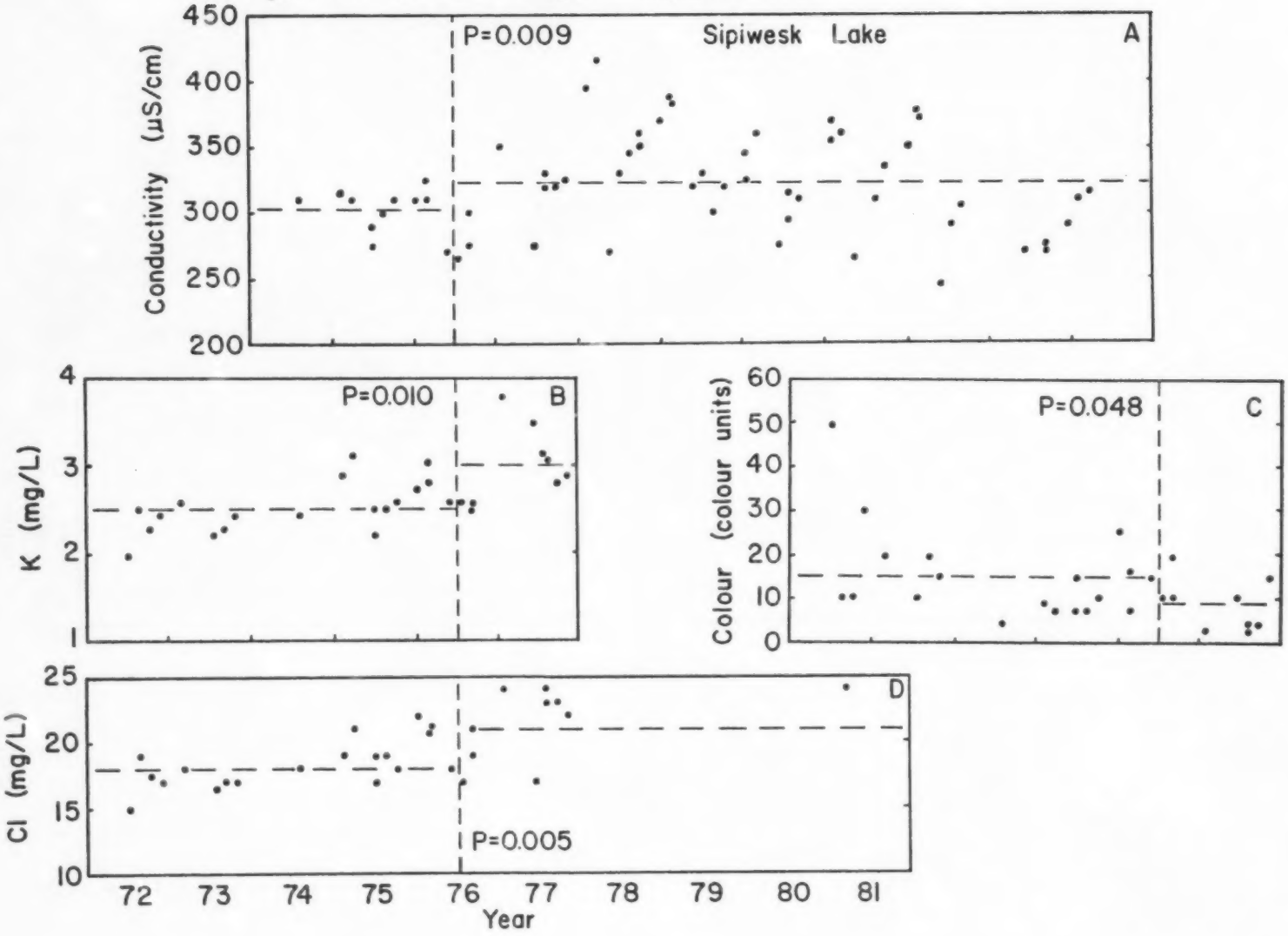
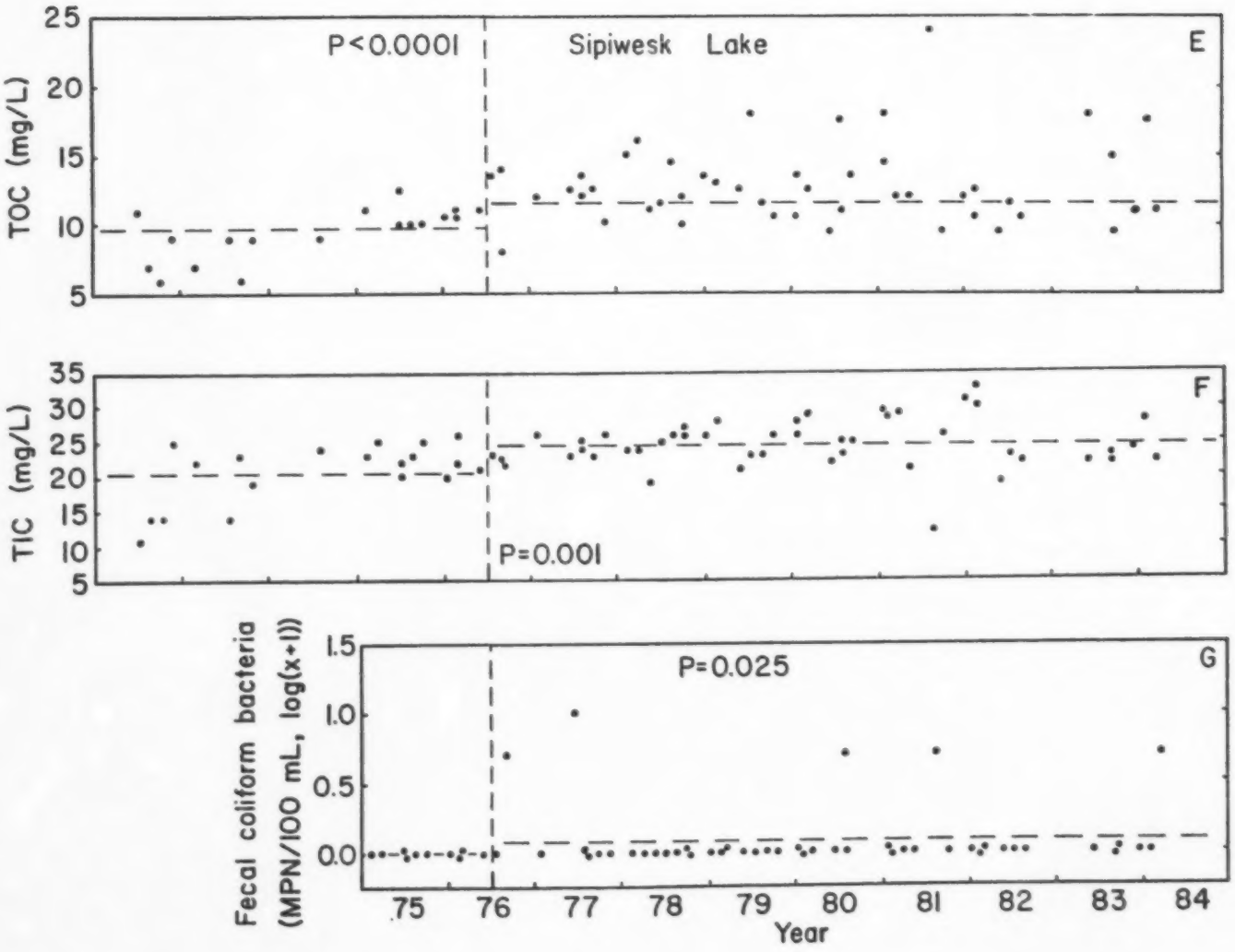

E
P=0.0002
Cross Lake settlement
TIC (mg/L)
F
P=0.012
Colour (colour units)
G
P=0.028
Turbidity (NTU)
74
75
76
77
78
79
80
81
82
83
84
Year

Figure 10. Chemical changes in Sipiwesk Lake.




P<0.0001
Sipiwesk Lake
E
TOC (mg/L)
25
20
15
10
5
F
TIC (mg/L)
35
30
25
20
15
10
5
P=0.001
G
P=0.025
Fecal coliform bacteria
(MPN/100 mL, log(x+1))
1.5
1.0
0.5
0.0
75
76
77
78
79
80
81
82
83
84
Year

the relative stability of the elevated levels (Figure 7 G), suggest that the increase in turbidity at Split Lake was real and was due to the increased flow of turbid water down the Burntwood River.

4.3.2 Upper Nelson River sites

The community of Norway House is located on the east arm of the upper Nelson River. Comparisons of data collected near the community before and after mid-1976 yielded statistically significant increases in total phosphorus, total organic carbon, total inorganic carbon, and turbidity, and decreases in sulphate and total Kjeldahl nitrogen (Table 2, Figure 8). At Cross Lake, where the east and west arms of the Nelson River merge, there were significant increases in potassium, chloride, total organic carbon, total inorganic carbon, and turbidity, and significant decreases in total Kjeldahl nitrogen and colour (Table 2, Figure 9). Further downriver at Sipiwesk Lake there was a marginally significant decrease in colour ($P = 0.048$), and significant increases in conductivity, potassium, chloride, total organic carbon, total inorganic carbon, and fecal coliform bacteria (Table 2, Figure 10).

Some of the water chemistry changes at the upper Nelson sites can be related to Lake Winnipeg regulation and channel construction. Shoreline degradation at Cross Lake was expected as a consequence of Lake Winnipeg regulation (Dickson 1975). Total organic carbon and total inorganic carbon increased from about 10 to 14 mg/L at all three upper Nelson sites, possibly due to shoreline erosion or channel construction exposing new soils to erosion. The reasons for the increases in potassium and chloride concentrations at Cross and Sipiwesk lakes are not known, but may also be related to erosion. The

causes of the decreases in colour at the two sites are also not known but appear, intuitively, to be unrelated to Lake Winnipeg regulation. Fecal coliform bacteria apparently increased in Sipiwesk Lake (from 0.0 to 0.2 per 100 mL) but the significance of this increase was relatively low (P = 0.025) and is probably an artifact of the zero standard deviation of the data from before mid-1976 (Figure 10 G, Appendix 3).

Turbidity increased at Norway House (Table 2), possibly a result of 2 Mile Channel construction which exposed new soils to erosion, and which could allow added sediment transport into Playgreen Lake during periods of strong south winds (predicted by LWCNR 1975). Turbidity increased at Cross Lake, probably because of decreased water levels in the lake (down by 1.7 m) which resulted in resuspension of the bottom sediments by wind (Bodaly et al. 1984a). However, as with Split Lake, high turbidities in 1972 that were excluded from data analysis give some indication that these turbidity changes were cyclic. This, and the relatively small increases in turbidity observed, suggest caution when interpreting the Norway House and Cross Lake turbidity data.

4.4 Lower Churchill River

Chemistry of the lower Churchill River was expected to change after the diversion because local tributaries would have a greater influence in determining lower Churchill River chemistry. Before the diversion, local streams contributed eight percent of the total flow at Missi Falls. After the diversion they were expected to contribute 37 percent of the total flow (Clough, in LWCNR 1975, Appendix 5, vol. 2-E). Conductivity, calcium, magnesium and total dissolved solids

were expected to increase after the diversion, and sodium concentrations and phosphorus loading were expected to decrease.

Water chemistry data from three tributaries of the lower Churchill River were used to help interpret changes in water chemistry in the lower Churchill River after the diversion. The tributaries were the Gauer, Oldman, and Little Churchill rivers (Figure 1). Data from July 1, 1976, to the end of 1977 were used, without consideration of different river volumes. Mean water chemistry was as follows: conductivity, 143 µS/cm; hydrogen ion concentration, 1.34×10^{-8} M/L; alkalinity, 72 mg($CaCO_3$)/L; calcium, 23 mg/L; total phosphorus, 22 µg/L; total organic carbon, 14 mg/L; total inorganic carbon, 16 mg/L; colour, 27 colour units; turbidity, 2 NTU; and total coliform bacteria, 9 organisms per 100 mL. Conductivity, alkalinity, calcium, phosphorus, total organic carbon, total inorganic carbon, and colour, were all greater than pre-diversion values at the Churchill River at Granville Lake, Missi Falls, and the Churchill water intake (cf. with Tables 1 and 3). Mean hydrogen ion concentrations of the tributaries were lower than pre-diversion values at these sites. Mean total coliform bacteria densities of the tributaries were higher than at Missi Falls and the Churchill water intake before diversion. Mean tributary turbidities were about the same as at Missi Falls before diversion.

After the diversion hydrogen ion concentration decreased and turbidity increased at Missi Falls (Table 3, Figure 11). Hydrogen ion concentration decreased because local waters of lower hydrogen ion concentration contributed more to water chemistry after the diversion. Similarly, conductivity, alkalinity, and calcium remained

Table 3. Comparison of data from before and after mid-1976 for the Churchill River at Missi Falls and at the Churchill water intake. Parameter abbreviations are defined in Figure 2.

Location		Cond. µS/cm	H^+ x10^{-9}M/L	Alkal. mg/L	Hard. mg/L	Ca mg/L	Mg mg/L	K mg/L	Na mg/L	Total P µg/L	Cl mg/L	SO_4 mg/L	TKN mg/L	NO_3-NO_2 mg/L	TOC mg/L	TIC mg/L	Colour units	Turb. NTU	NFR mg/L	T.Coli MPN/100 mL	F. Coli MPN/100 mL
Churchill Water Intake	P	.016	.0004	.001	.117	.228				.002				.354	.0004	.0001	.701	.117		.0003	
	$\bar{x}_1$	118	1.98	51	51	15	a	a	a	17	a	a	-	0.24	9	11	18	3.4	a	2	-
	$\bar{x}_2$	130	1.15	60	57	16				35				0.12	12	14	16	5.8		42	
Missi Falls	P	.087	.032	.969	.978	.511				.627		.689		.786	.477	.133	.286	.0001		.948	.690
	$\bar{x}_1$	116	2.40	49	44	12.4	a	a	a	18	a	4	-	0.06	9	10	11	1.9	a	2	0.3
	$\bar{x}_2$	105	1.74	49	44	13.0				20		4		0.05	8	11	9	6.0		3	0.2

P = probability of equality of $\bar{x}_1$ and $\bar{x}_2$, t-test.
$\bar{x}_1$ = mean of data to June 30, 1976.
$\bar{x}_2$ = mean of data from July 1, 1976.
- = insufficient data.
a = too many data < detection limit.

Figure 11. Chemical changes in the Churchill River at Missi Falls.

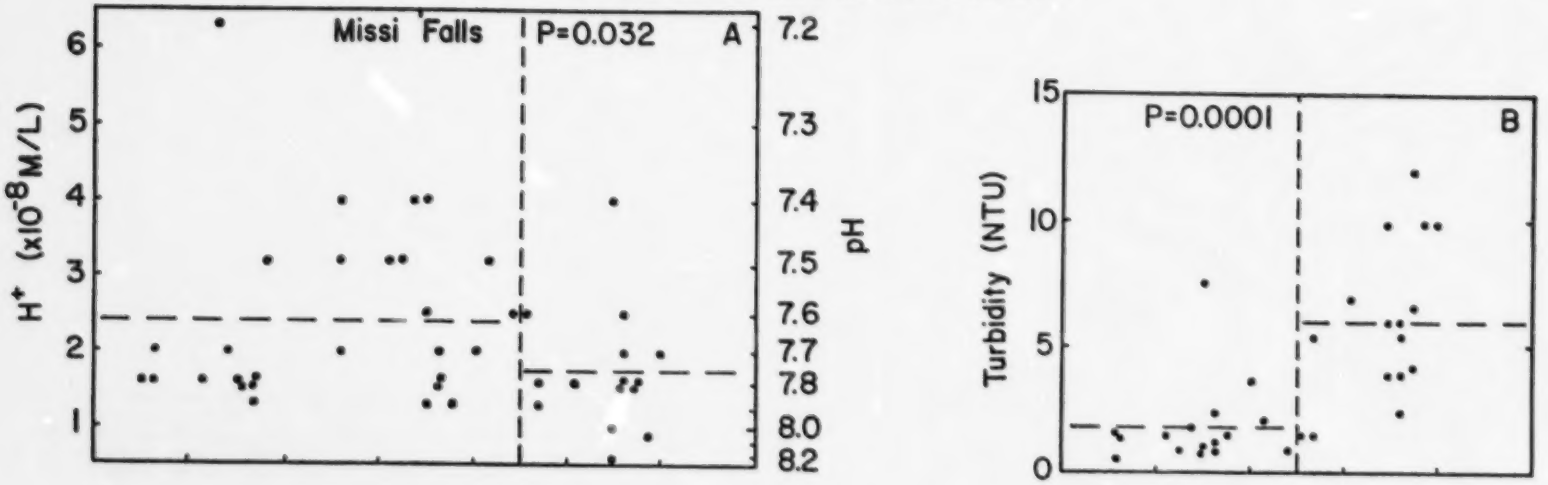
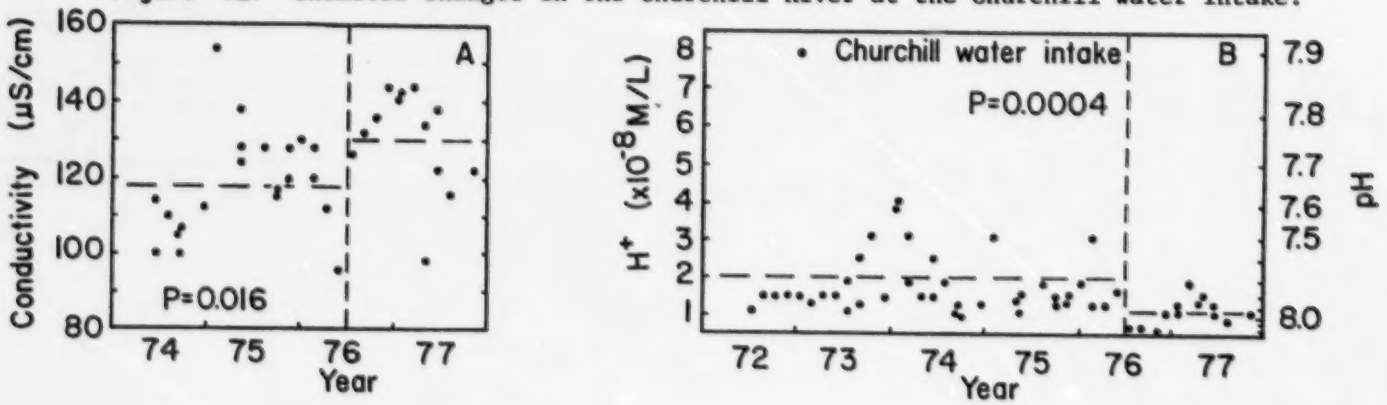
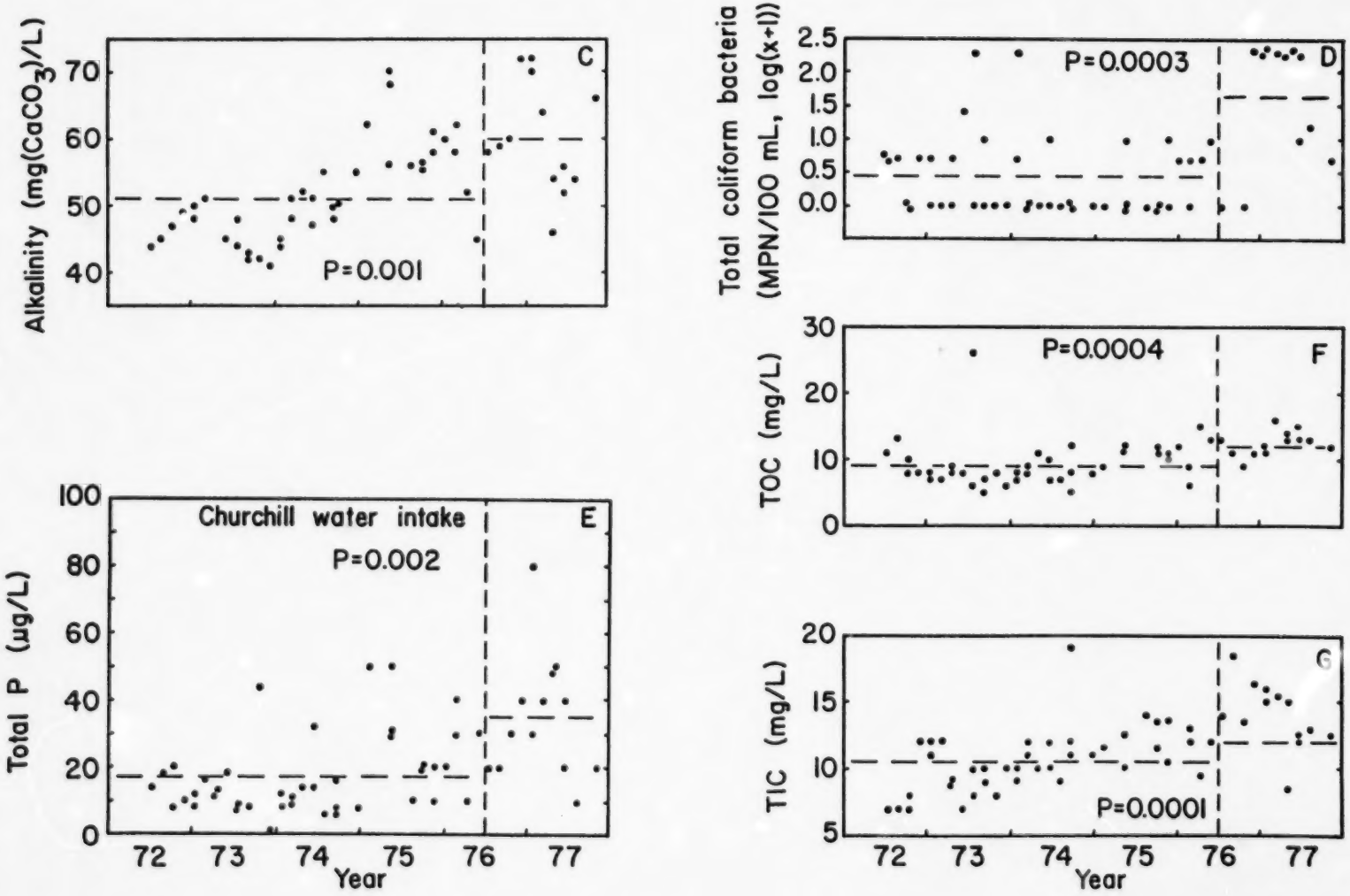


Figure 12. Chemical changes in the Churchill River at the Churchill water intake.




Alkalinity (mg($CaCO_3$)/L)
C
P=0.001
Total coliform bacteria (MPN/100 mL, log(x+1))
D
P=0.0003
TOC (mg/L)
F
P=0.0004
Total P (µg/L)
Churchill water intake
E
P=0.002
TIC (mg/L)
G
P=0.0001
Year
72 73 74 75 76 77

stable because of the increased influence of local water. Turbidity increased at Missi Falls due to erosion in Southern Indian Lake. Phosphorus concentrations remained stable at Missi Falls, in contrast with the increases seen at the Churchill water intake and between Granville Lake and Thompson (Figure 2). This tends to support the prediction of the LWCNR (1975) that phosphorus concentrations would decrease at Missi Falls because of the diversion of nutrient-rich Churchill River water.

After the diversion conductivity, alkalinity, total phosphorus, total organic carbon, total inorganic carbon, and total coliform bacteria increased and hydrogen ion concentration decreased at the Churchill water intake (Table 3, Figure 12). In general these changes were a result of the increased influence of local waters to lower Churchill River chemistry. The mean value of total coliform bacteria of the Gauer, Oldman, and Little Churchill rivers was 9 organisms per 100 mL, not high enough to explain the whole increase from a mean of 2 to a mean of 42 organisms per 100 mL at the Churchill water intake. While speculative, tributaries closer to the water intake may have had higher total coliform bacteria counts than these three tributaries. Similarly, the post-diversion phosphorus concentration at the Churchill water intake (35 µg/L; up from 17 µg/L) was higher than the pooled tributary mean (22 µg/L). Other tributaries to the lower Churchill River might have supplied the additional phosphorus. Another possible phosphorus source is erosion from newly exposed river banks (Ingram et al. 1985) in the lower Churchill River.

In a similar analysis of data from Fidler Lake, below

Missi Falls, Guilbault et al. (1979) found increases in hardness, calcium, phosphorus, and total inorganic carbon, all of which can be explained by the increased importance of local drainage to lower Churchill River chemistry after the diversion. They found an increase in colour (from 9.9 to 18.6 relative units, $P \simeq < 0.002$), which was not seen in this analysis of Churchill water intake data. Their change in colour may have been a local phenomenon or an artifact of few data to assess, but it does agree with the high mean colour of the Gauer, Oldman, and Little Churchill rivers (27 colour units). Turbidity increased from 2.1 to 10.0 JTU ($P \simeq < 0.001$) at Fidler Lake (Guilbault et al. 1979), likely because of increased turbidity in Southern Indian Lake.

4.5 Changes in drinking water quality

Canadian drinking water quality guidelines exist for a wide range of parameters (Health and Welfare Canada, 1978). However, guidelines do not exist for all parameters that were observed to change during the period of statistical comparison. For such parameters, guidelines are available for only colour, turbidity and coliform bacteria. The maximum colour acceptable in drinking water is established for aesthetic reasons at 15 colour units (Health and Welfare Canada 1978). In the period of comparison, there were statistically significant decreases in colour to below 15 colour units at Sipiwesk Lake and Cross Lake (Table 2). Colour was always greater than 15 units at Nelson House, Thompson, Split Lake, Norway House, and the Churchill water intake. There was some indication of decreased colour at Nelson House, Thompson, and Split Lake because of increased flow of less-coloured water from the diversion, but the post-diversion

values were still greater than 15 colour units and the changes were not statistically significant.

Five NTU is the maximum acceptable level of turbidity in drinking water (Health and Welfare Canada 1978). High turbidity can protect micro-organisms from the effects of disinfection, so water treatment is needed to reduce excessive turbidity before drinking water supplies are disinfected. The Churchill River diversion caused statistically significant increases in turbidity to above 5 NTU at South Indian Lake community and Missi Falls (Tables 1 and 3). Turbidity increased to 5.8 NTU at the Churchill water intake, but this was not a statistically significant change. Turbidity was always unacceptable at Thompson and at the Nelson River sites, but worsened at Split Lake, Cross Lake, and Norway House after mid-1976 (Tables 1 and 2). There was no increase in turbidity in Sipiwesk Lake (Table 2).

Surface waters are susceptible to microbial contamination (i.e. by wildlife), hence all drinking water drawn from surface water should be disinfected as a minimum treatment (Manitoba Regulation P210-R3, Public Health Act, Division VII, Section 57). An additional level of treatment is required if ten percent of samples exceed 100 total coliform bacteria per 100 mL (Health and Welfare Canada 1978; Williamson 1983). At Thompson and at Cross Lake settlement this criterion was exceeded both before (20 and 14%, respectively), and after mid-1976 (17 and 10%, respectively), although the mean number of bacteria did not change (Tables 1 and 2). At Granville Lake 25% of the bacterial samples exceeded 100 organisms per 100 mL before mid-1976, but none were greater than 100 organisms per 100 mL after mid-1976. This was reflected in the change in means (Table 1),

although the decrease was not statistically significant. Fourteen percent of the pre-diversion total coliform samples at South Indian Lake community were above 100 organisms per 100 mL, but none were above 100 organisms per 100 mL after diversion. This agrees with the statistically significant change in total bacterial means (Table 1) and was likely due to increased flushing past the community after Churchill River diversion. At the Churchill water intake the number of total coliform bacteria samples above 100 organisms per 100 mL increased from five percent before diversion to fifty-eight percent after diversion, which agrees with the statistically significant increase in total coliform mean (Table 3). This change was probably due to the increased contribution to water chemistry of tributaries close to the Churchill water intake.

Additional treatment of drinking water drawn from surface waters is required if ten percent of fecal coliform bacteria samples exceed 10 organisms per 100 mL (Health and welfare Canada 1978; Williamson 1983). This criterion was exceeded at the Burntwood River at Thompson after the Churchill River diversion (23% of samples were > 10 organisms per 100 mL) whereas before the diversion no samples exceeded the guideline. The increase in fecal coliform mean was not statistically significant (Table 1). At Split Lake community ten percent of the samples were greater than 10 organisms per 100 mL both before and after mid-1976. A statistically significant change was not observed in fecal bacterial means (Table 3). Although there was a small statistically significant increase in fecal bacterial means at Sipiwesk Lake, none of the samples from before or after mid-1976 exceeded 10 organisms per 100 mL.

The bacterial data suggest that treatment in addition to disinfection is now required for water drawn from the Burntwood River at Thompson, Split Lake near Split Lake settlement, Cross Lake near Cross Lake settlement, and the Churchill River near Churchill. Turbidity data suggest that the extra level of treatment is also required for water drawn from Southern Indian Lake near South Indian Lake community, the Churchill River at Missi Falls, from Sipiwesk Lake, and the Nelson River near Norway House. The bacterial and turbidity data also suggest that the additional level of treatment for drinking water was needed before mid-1976 at all ten sites except Nelson House, Missi Falls, and the Churchill water intake.

5.0 Conclusions

Some water chemistry changes along the Churchill, Burntwood, and Nelson rivers can reasonably be attributed to the Churchill River diversion and Lake Winnipeg regulation, in spite of analytical method changes and other changes unrelated to these project. Water chemistry along the diversion path changed because of flooding and erosion, and increased flows of softer Churchill River water. Water chemistry at Split Lake was affected by the increased flow of turbid, softer water in the Burntwood River, and was also affected by changes in the upper Nelson River. Increases in turbidity and total organic and inorganic carbon were observed at sampling sites located on the upper Nelson River. These changes may have been a result of Lake Winnipeg regulation. Water chemistry in the lower Churchill River changed because of increased turbidity from flooding and erosion in Southern Indian Lake and because local drainage had more influence on water chemistry once most of the Churchill River flow was diverted southward.

In general, predictions of water chemistry changes caused by the hydroelectric projects were good, especially those related to changes in water flow. This is in marked contrast with biological predictions for Southern Indian Lake, which became less reliable as the trophic level increased (Hecky et al. 1984). Some predictions, such as oxygen depletion in lakes because of decomposing vegetation, could not be tested because of too few data. Consistent methods and sampling would have increased the usefulness of the type of data analysis done here.

Hydroelectric development is often labelled non-polluting, but it can have large effects on the environment (Efford 1975). A parameter such as conductivity at Split Lake will continue to be a relatively simple function of mixing two volumes of water of different conductivities, but turbidity at Missi Falls or South Indian Lake will be more difficult to predict. Newbury and McCullough (1984) suggested that high turbidity in Southern Indian Lake will persist for about thirty-five years, the minimum estimated period for bank stabilization. Day et al. (1982) have determined that after forty-three years, erosion of glaciolacustrine shores is still a problem within the Long Lake diversion in northwestern Ontario. The Lake Winnipeg, Churchill and Nelson Rivers Study Board collected valuable background information for the evaluation of the consequences of the Churchill River diversion (Hecky et al. 1984). Continued monitoring and interpretation of water chemistry is necessary in order to better understand the effects of hydroelectric development in northern Canada.

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Appendix 1. Summary of time period used for certain parameters and reasons for exclusion of other parameters from statistical analysis. A.A.S. = Atomic absorption spectroscopy.

Parameter	Time period used or reason for exclusion from data analysis	
Conductivity	from June 1, 1974	poor temperature compensation before June, 1974
Calcium	from November 1, 1974	changed from colorimetric method to A.A.S.
Magnesium	from October 1, 1974	changed from colorimetric method to A.A.S.
Total Kjeldahl nitrogen	from May 1, 1972	changed to colorimetric phenate method.
Nitrate-nitrite	from January 1, 1974	changed to cadmium reduction method
Total organic carbon	from April 1, 1972	changed to Beckman total carbon analyzer
Total inorganic carbon	from April 1, 1972	changed to Beckman total carbon analyzer
Turbidity	from April 1, 1974	changed from JTU to NTU
Temperature	too highly influenced by sampling date	
Aluminum		I.D.
Iron		changed from colorimetric method to A.A.S. in September 1975
Cadmium		I.D.
Copper		changed to solvent extraction with MIBK in February 1975
Lead		changed to solvent extraction with MIBK in February 1975
Nickel		I.D.
Zinc		a
Manganese		a
Silica		I.D.
Mercury		I.D.
Dissolved oxygen		I.D.
Biological oxygen demand		I.D.
Chemical oxygen demand		I.D.
Ortho-phosphorus		I.D.
Chlorophyll a		I.D.
Ammonia		I.D.
Total residue		data only available for 1975, 1976, and 1977
Filterable residue		data only available for 1975, 1976, and 1977

I.D. = only one or two of the 10 sites in Figure 2 had enough data for statistical analysis.

a = none of the 10 sites in Figure 2 had enough data suitable for analysis when the number of data below the detection limit was considered.

Appendix 2. Comparison of data from before and after mid-1976 for the Churchill River at Otter Rapids and below Wasawekasik Lake, Saskatchewan. Parameter abbreviations are defined in Figure 2.

Location		Cond. µS/cm	H^+ x10^{-8} µg/L	Alkal. mg/L	Hard. mg/L	Ca mg/L	Mg mg/L	K mg/L	Na mg/L	Total P µg/L	Cl mg/L	SO_4 mg/L	TKN mg/L	NO_3-NO_2 mg/L	TOC mg/L	TIC mg/L	Colour units	Turb. JTU	NFR mg/L	T.Coli MPN/100 mL	F. Coli MPN/100 mL
Churchill River at Otter Rapids	P	.003	.966	.0003				.409	.676	.770	.806	.325			<.0001	.438	.017	.809			
	$\bar{X}_1$	172	1.76	74	-	-	-	1.8	5.6	21	2.5	4	-	-	11	15	19	1.7	-	-	-
	$\bar{X}_2$	147	1.77	64				1.6	5.5	22	2.5	3			9	15	12	1.6			
Churchill River below Wasawekasik Lake	P	<.0001	.337	<.0001	<.0001	<.0001	.0001	<.0001	<.0001	.030	.001	.004	.008		<.0001	<.0001		.804	.320	.252	.078
	$\bar{X}_1$	115	2.43	52	53	13	5	1.3	3.8	14	1.5	3.4	0.4	a	9	11	a	3.2	4	4_b	0.7_b
	$\bar{X}_2$	83	2.73	34	36	9	4	1.0	2.9	20	1.1	2.8	0.3		6	8		3.3	3	3	1.3

P = probability of equality of $\bar{X}_1$ and $\bar{X}_2$, t-test.
$\bar{X}_1$ = mean of data to June 30, 1976.
$\bar{X}_2$ = mean of data from July 1, 1976.
- = insufficient data.
a = too many data < detection limit.
b = membrane filter method

Appendix 3. Standard deviations and number of data for sites and parameters considered in this study. The first column under each parameter contains the standard deviations; the second column contains the number of data used.

Location	Cond.		H^+		Alkal.		Hard.		Ca		Mg		K		Na		Total P		Cl		SO_4		TKN		Nitr.		TOC		TIC		Colour		Turb.		NFR		T.Coli*		F.Coli*	
A 1	14	21	1.23	41	7	40	8	42	2	15	-	-	-	-	-	-	12	42	-	-	-	-	-	-	0.51	22	4	41	2	41	12	41	4.7	21	-	-	4	40	-	-
2	13	13	0.39	13	8	13	14	13	3	13	-	-	-	-	-	-	19	13	-	-	-	-	-	-	0.24	13	2	13	2	13	8	13	4.1	13	-	-	10	12	-	-
B 1	24	16	1.16	28	9	24	8	20	3.0	13	-	-	-	-	-	-	19	24	2	29	-	-	-	-	0.06	16	2	28	3	24	6	24	1.7	16	-	-	6	16	2	16
2	8	16	0.78	16	5	16	8	9	1.6	32	-	-	-	-	-	-	6	35	2	32	-	-	-	-	0.12	16	2	32	1	36	6	16	3.2	16	-	-	3	9	2	9
C 1	20	8	0.74	29	11	28	-	-	-	-	-	-	0.5	29	1.0	29	9	6	0.4	10	1	6	-	-	-	-	1	22	3	22	10	24	0.7	9	-	-	-	-	-	-
2	17	30	0.83	30	7	30	-	-	-	-	-	-	1.0	30	0.6	30	7	30	0.9	30	1	30	-	-	-	-	2	27	2	18	9	20	0.8	29	-	-	-	-	-	-
D 1	15	20	1.28	20	7	20	7	19	3	15	1	11	0.2	20	0.5	20	6	20	0.4	20	1	20	0.2	18	-	-	1	20	2	20	-	-	1.6	20	4	14	3	13	2	19
2	23	72	1.06	72	8	71	8	41	2	72	1	29	0.2	72	0.6	72	19	70	0.3	72	1	72	0.1	15	-	-	2	41	2	17	-	-	2.8	71	2	72	2	69	1	69
E 1	19	11	1.24	28	12	27	14	23	3	7	-	-	0.2	28	0.7	28	5	24	0.5	28	1	28	0.2	21	0.07	12	2	25	3	25	9	27	1.9	12	-	-	8	12	2	10
2	19	40	2.55	41	6	24	10	6	3	24	-	-	0.3	6	0.6	6	6	41	0.2	6	4	6	0.2	41	0.09	41	2	20	2	20	9	6	2.8	19	-	-	3	33	2	33
F 1	26	11	0.99	22	10	22	13	22	5	10	-	-	-	-	-	-	9	22	-	-	-	-	0.4	9	-	-	2	22	2	22	5	22	2.1	11	-	-	9	22	3	22
2	10	31	0.89	32	4	22	10	9	3	22	-	-	-	-	-	-	8	32	-	-	-	-	0.1	23	-	-	2	32	1	32	4	9	3.9	18	-	-	3	31	2	30
G 1	24	12	1.28	25	15	25	17	24	6	10	2	10	-	-	-	-	10	26	-	-	-	-	0.1	13	0.06	12	2	25	5	25	11	26	2.4	12	-	-	5	21	1	19
2	22	47	1.81	48	12	30	9	9	5	28	2	28	-	-	-	-	16	48	-	-	-	-	0.1	39	0.11	48	2	46	3	48	4	9	2.9	23	-	-	3	46	2	45
H 1	15	25	1.14	62	9	62	8	55	3	11	1	12	-	-	-	-	18	40	-	-	1	61	-	-	0.09	29	2	48	3	47	13	61	12	29	8	23	8	5	4	5
2	15	60	1.16	62	8	45	8	23	5	45	1	31	-	-	-	-	28	63	-	-	3	23	-	-	0.16	63	5	41	2	41	28	23	8	38	13	53	8	48	6	48
I 1	22	10	0.50	25	14	25	16	25	3	9	2	9	0.7	24	3	24	110	22	3	25	5	24	0.2	14	0.07	10	2	25	5	25	10	25	4.2	10	8	16	4	23	3	21
2	39	44	0.35	44	9	27	7	9	5	28	2	27	0.4	9	3	9	9	44	5	9	5	9	0.1	35	0.09	44	2	44	3	44	3	9	5.1	22	6	44	3	42	3	42
J 1	17	11	0.38	19	10	19	11	19	3	10	1	10	0.3	19	2	19	16	17	2	19	4	19	0.2	8	0.04	11	2	18	4	19	11	19	4.6	11	-	-	2	10	0	10
2	40	48	0.34	48	13	30	16	10	6	29	2	30	0.4	9	3	9	11	48	3	10	8	9	0.1	39	0.13	48	3	47	4	47	6	9	3.7	24	-	-	3	46	2	46
K 1	31	20	2.08	41	14	41	17	41	4	15	2	13	1.1	40	4	41	61	36	4	41	5	39	0.2	24	0.19	19	3	39	5	39	9	40	2.7	22	8	20	12	35	3	32
2	40	50	0.75	50	13	33	9	12	4	32	2	32	0.6	11	5	11	12	50	4	11	5	11	0.1	39	0.10	47	4	50	4	50	5	11	5.4	26	7	50	5	49	3	45
L 1	27	12	0.64	30	15	30	15	30	6	9	2	9	0.4	30	3	30	13	24	4	30	4	30	0.4	17	-	-	4	30	5	30	10	30	2.5	13	-	-	4	26	3	25
2	58	48	0.58	48	15	30	14	10	5	30	2	30	0.8	9	4	9	12	18	5	9	5	9	0.1	39	-	-	7	48	4	48	11	9	1.9	23	-	-	6	46	3	46

A = Churchill water intake
B = Missi Falls
C = Churchill R. at Otter Rapids
D = Churchill R. below Wasawakasik L
E = Churchill R. at Granville L.
F = South Indian Lake community
G = Nelson House community
H = Burntwood R. at Thompson
I = Split Lake settlement
J = Sipiwesk Lake
K = Cross Lake settlement
L = Norway House community

* = $\bar{x} \pm$ S.D.
1 = to June 30, 1976
2 = from July 1, 1976
1 S.D. n
2 S.D. n